

Energetics of the molecular gas in the H₂ luminous radio galaxy 3C 326: Evidence for negative AGN feedback[★]

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Received 21 September 2009 / Accepted 17 March 2010

ABSTRACT

We present a detailed analysis of the gas conditions in the H₂ luminous radio galaxy 3C 326 N at $z \sim 0.1$, which has a low star-formation rate ($SFR \sim 0.07 M_{\odot} \text{ yr}^{-1}$) in spite of a gas surface density similar to those in starburst galaxies. Its star-formation efficiency is likely a factor ~ 10 – 50 lower than those of ordinary star-forming galaxies. Combining new IRAM CO emission-line interferometry with existing Spitzer mid-infrared spectroscopy, we find that the luminosity ratio of CO and pure rotational H₂ line emission is factors 10 – 100 lower than what is usually found. This suggests that most of the molecular gas is warm. The Na D absorption-line profile of 3C 326 N in the optical suggests an outflow with a terminal velocity of $\sim 1800 \text{ km s}^{-1}$ and a mass outflow rate of 30 – $40 M_{\odot} \text{ yr}^{-1}$, which cannot be explained by star formation. The mechanical power implied by the wind, of order $10^{43} \text{ erg s}^{-1}$, is comparable to the bolometric luminosity of the emission lines of ionized and molecular gas. To explain these observations, we propose a scenario where a small fraction of the mechanical energy of the radio jet is deposited in the interstellar medium of 3C 326 N, which powers the outflow, and the line emission through a mass, momentum and energy exchange between the different gas phases of the ISM. Dissipation times are of order 10^{7-8} yrs, similar or greater than the typical jet lifetime. Small ratios of CO and PAH surface brightnesses in another 7 H₂ luminous radio galaxies suggest that a similar form of AGN feedback could be lowering star-formation efficiencies in these galaxies in a similar way. The local demographics of radio-loud AGN suggests that secular gas cooling in massive early-type galaxies of $\geq 10^{11} M_{\odot}$ could generally be regulated through a fundamentally similar form of “maintenance-phase” AGN feedback.

Key words. galaxies: evolution – galaxies: ISM – galaxies: jets – radio continuum: galaxies – radio lines: galaxies

1. Introduction

Molecular gas plays a critical role for our growing understanding of galaxy evolution. It often dominates the mass budget of the interstellar medium in galaxies, and is most closely related to the intensity at which galaxies form stars (e.g., Kennicutt 1998). Being strongly dissipative, it is also particularly susceptible to the astrophysical processes that drive galaxy evolution – interactions, or feedback from starbursts and AGN – and therefore plays a key role for our understanding of how these processes regulate star formation and galaxy assembly.

It has only recently been recognized that powerful AGN may play a significant role in regulating galaxy growth over cosmological timescales by suppressing gas accretion and star formation (e.g., Silk & Rees 1998; Friaca & Terlevich 1998; Scannapieco & Oh 2004; Springel et al. 2005; Bower et al. 2006; Croton et al. 2006; Ciotti & Ostriker 2007; Merloni & Heinz 2008). Such AGN “feedback” would help resolve some of the remaining discrepancies between hierarchical models of galaxy evolution – implying a rather gradual assembly of massive

galaxies – and observations, which suggest that massive galaxies formed most of their stars at high redshift, whereas star formation at later epochs was strongly suppressed. Observationally, a picture is emerging where radio jets may play a large role in transforming the energy ejected by the AGN into kinetic and thermal energy of the interstellar medium of the host galaxy. Observations of radio-loud AGN (e.g., Heckman et al. 1991b,a; Morganti et al. 2005; Emonts et al. 2005; Best et al. 2005, 2006; Nesvadba et al. 2006, 2007; McNamara & Nulsen 2007; Nesvadba et al. 2008; Holt et al. 2008; Baldi & Capetti 2008; Fu & Stockton 2009; Humphrey et al. 2009) and a large number of hydrodynamical simulations (e.g., Krause 2005; Saxton et al. 2005; Heinz et al. 2006; Sutherland & Bicknell 2007; Merloni & Heinz 2007; Antonuccio-Delogu & Silk 2008) suggest that radio-loud AGN inject a few percent of their mechanical energy into the ambient gas, parts of which produce significant outflows of warm gas (Morganti et al. 2003, 2005; Emonts et al. 2005; Nesvadba et al. 2006, 2007; Holt et al. 2008; Nesvadba et al. 2008; Fu & Stockton 2009). However, most previous studies focused on the warm and hot gas at temperatures $\geq 10^4 \text{ K}$, and did not address the impact on the molecular phase, which is a

[★] Based on observations carried out with the IRAM Plateau de Bure Interferometer.

serious limitation if we want to understand how the radio-loud AGN may regulate star formation in the host galaxy.

Observations with the Spitzer IRS spectrograph recently revealed a significant number of “H₂-luminous” galaxies, where the molecular gas does not appear associated with star formation (Appleton et al. 2006; Egami et al. 2006; Ogle et al. 2007, 2008, 2010; de Messières et al. 2009; Sivanandam et al. 2009, see also Haas et al. 2005a)¹. The mid-infrared spectra of H₂-luminous galaxies are dominated by bright, pure rotational emission lines of warm molecular hydrogen, ($\mathcal{L}(\text{H}_2) = 10^{40} - 10^{43} \text{ erg s}^{-1}$), while classical star-formation indicators like a bright infrared continuum, mid-infrared lines of [NeII] and [NeIII], and PAH bands are weak or absent. Interestingly, Ogle et al. (2010) find that 30% of their radio-loud AGN taken from the 3CR are H₂ luminous, suggesting this may be a common phenomenon which could be related to interactions with the radio source.

To test this hypothesis and to evaluate possible consequences for the gas properties and star formation in the host galaxy, we have started CO emission-line observations of H₂ luminous radio galaxies with the IRAM Plateau de Bure Interferometer. Our goal is to constrain the physical properties and masses of the multiphase warm and cold gas in these galaxies, and to measure the gas kinematics. Here we present a detailed analysis of the multiphase gas content, energetics, and dissipation times of the H₂-luminous radio galaxy 3C 326 N at $z = 0.09$ (Ogle et al. 2007, 2008, 2010), which has particularly high H₂/PAH ratios. This analysis is based on our new CO(1–0) observations, as well as existing mid-infrared Spitzer and SDSS optical spectroscopy. Specifically we address three questions: what powers the H₂ emission in this galaxy? What is the physical state of the molecular gas, and perhaps most importantly, why is 3C 326 N not forming stars?

We find that the interstellar medium of 3C 326 N has very unusual physical properties, where the warm molecular gas may dominate the overall molecular gas budget (Sect. 4) and where the emission-line diagnostics suggest that the molecular as well as the ionized gas may be mainly excited by shocks (Sect. 3) giving rise to luminous line emission at UV to mid-infrared wavelengths. We also identify a significant outflow of neutral gas from Na D absorption profiles, which cannot be explained by star formation (Sect. 5). We propose a physical framework in which these observations can be understood as a natural consequence of the energy and momentum coupling between the gas phases, which is driven by the mechanical energy injection of the radio jet (Sect. 6). This scenario is an extension of the classical “cocoon” model (e.g., Scheuer 1974; Begelman & Cioffi 1989) explicitly taking into account the multiphase character of the gas, with an emphasis on the molecular gas. We use our observational results to quantify some of the parameters of this scenario, including, perhaps most importantly, the dissipation time of the turbulent kinetic energy of the gas, and find that it is self-consistent and in agreement with the general characteristics of radio-loud AGN.

3C 326 N shows evidence for a low star-formation efficiency leading to a significant offset from the Schmidt-Kennicutt relationship of ordinary star-forming galaxies by factors 10–50, which is similar to other H₂ luminous radio galaxies with CO observations in the literature, as would be expected if 3C 326 N was a particularly clear-cut example of a common, underlying

physical mechanism that is throttling star formation (Sect. 7). Long dissipation times suggest that the gas may remain turbulent over timescales of 10^{7-8} years, of order of the lifetime of the radio source, or perhaps even longer (Sect. 6.3), while the energy supplied by the radio source may be sufficient to keep much of the gas warm for a Hubble time (Sect. 8) as required during the maintenance phase of AGN feedback, assuming typical duty cycles of order 10^8 yrs.

Throughout the paper we adopt a $H_0 = 70 \text{ km s}^{-1}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ cosmology. In this cosmology, the luminosity distance to 3C 326 N is $D_L^{326N} = 411 \text{ Mpc}$. One arcsecond corresponds to a projected distance of 1.6 kpc.

2. Observations

2.1. The H₂ luminous radio galaxy 3C 326 N

We present an analysis of the powerful H₂ luminous radio galaxy 3C 326 N at $z \sim 0.1$ (Ogle et al. 2007, 2010). Pure rotational, mid-infrared H₂ lines in 3C 326N have an extraordinary luminosity and equivalent width (Ogle et al. 2007). The total emission-line luminosity of 3C 326N is $L(\text{H}_2) = 8.0 \pm 0.4 \times 10^{41} \text{ erg s}^{-1}$ (integrated over the lines S(1) to S(7)), corresponding to $17 \pm 2\%$ of the infrared luminosity integrated from 8–70 μm . This is the most extreme ratio found with Spitzer so far. The H₂ line emission is not spatially or spectrally resolved, implying a size $< 4''$ ($\sim 6 \text{ kpc}$ at the distance of the source), and a line width $FWHM \leq 2500 \text{ km s}^{-1}$.

3C 326 N is remarkable in that it does not show evidence for strong star formation, in spite of a significant molecular gas mass of $\sim 10^9 M_\odot$ (Ogle et al. 2007, 2010). This mass corresponds to a mean surface density of warm H₂ within the slit of the short-wavelength spectrograph of Spitzer of $30 M_\odot \text{ pc}^{-2}$, a few times larger than the total molecular gas surface density of the molecular ring of the Milky Way (Bronfman et al. 1988). Generally, galaxies with similarly large molecular gas masses show vigorous starburst or AGN activity. However, in 3C 326 N the luminosity of the PAH bands and 24 μm dust continuum suggest a star-formation rate of only $\sim 0.07 M_\odot \text{ yr}^{-1}$, about 2% of that in the Milky Way. Given this large amount of molecular gas and the high mass surface density, the bolometric AGN luminosity of 3C 326 N is also remarkably low.

3C 326 N has a Mpc-sized FR II radio source, which is relatively weak for this class, with a radio power of $2.5 \times 10^{26} \text{ W Hz}^{-1}$ at 327 MHz. There is some confusion in the literature regarding which galaxy, 3C 326 N or the nearby 3C 326 S is associated with the radio lobes. Both candidates have detected radio cores and the extended radio lobes make it difficult to uniquely associate one or the other component with the radio source. Rawlings et al. (1990) argue that 3C 326 N is the more plausible candidate, having the brighter stellar continuum (and greater stellar mass, Ogle et al. 2007). Only 3C 326 N has luminous [OIII] $\lambda 5007$ line emission consistent with the overall relationship between [OIII] $\lambda 5007$ luminosity and radio power (Rawlings et al. 1990). The core of 3C 326 N appears unresolved at 8.5 GHz with a $2''$ beam (Rawlings et al. 1990). We discuss the age and kinetic power of the radio source of 3C 326 Sect. 4.2.

2.2. CO millimeter interferometry

CO(1–0) emission-line observations of 3C 326 were carried out with the IRAM Plateau de Bure Interferometer (PdBI) in two runs in January and July/August 2008 with different configurations. In January, we used the narrow-band

¹ Ogle et al. (2007, 2010) propose to introduce a new empirical classification based on this H₂ excess, and refer to such targets as “Molecular Hydrogen Emission Galaxies”, MOHEGs.

and dual-polarisation mode, corresponding to a band width of 950 MHz, or 2740 km s⁻¹, with a channel spacing of 2.5 MHz. The 6 antennae of the PdBI were in the BC configuration at a central frequency of 105.85 GHz, corresponding to the observed wavelength of the CO(1–0) line at a redshift of $z = 0.090$. The final on-source integration time for this run was 6.7 hrs (discarding scans with atmospheric phase instabilities). The *FWHP* of the synthesized beam in the restored map is $2.5'' \times 2.1''$ with a position angle of 23°. Only data from this run were used for the CO emission-line measurements.

The presence of a 3 mm non-thermal continuum from the radio source and relatively narrow receiver bandwidth made it difficult to rule out a possible contribution of a very broad CO(1–0) line ($FWHM > 1000$ km s⁻¹) from the January 2008 data alone. We therefore re-observed 3C 326 N in July and August 2008 with the goal of carefully estimating the continuum level, taking advantage of the 1.75 GHz bandwidth in the wide-band single-polarisation mode, corresponding to 4956 km s⁻¹. For these observations we used 5 antennae in the compact D-configuration. The final on-source integration time for this run was 5.2 h (again, discarding scans with strong atmospheric phase instabilities). We detected the millimeter continuum at a level of $S_{3\text{ mm}} = 0.99 \pm 0.05$ mJy at the centimeter position of the radio source measured by Rawlings et al. (1990).

Data reduction and analysis relied on GILDAS (Pety 2005). The flux was calibrated against MWC349 and against reference quasars whose flux is monitored with the PdBI. We removed the continuum by assuming a point source at the position of 3C 326 N with a flat spectrum of 1 mJy in the *uv*-plane. The data were then averaged in 71 km s⁻¹-wide velocity channels.

2.3. CO line emission

We show the continuum-free CO(1–0) emission-line map of 3C 326 N in the inset of Fig. 1, integrated over 637 km s⁻¹ around the line centroid. The central position is slightly offset from the millimeter continuum position (by $0.37'' \times 0.80''$ in right ascension and declination, respectively), corresponding to 1/3 to 1/6 of the beam size, respectively. Given the relatively low signal-to-noise ratio, this offset is not significant.

We measured the CO(1–0) line flux in different apertures and in the *uv* plane to investigate whether the line emission may be spatially extended, finding a larger flux for elliptical Gaussian models than for a point source. This may suggest that the source is marginally spatially extended with a size comparable to our $2.5'' \times 2.1''$ beam. Results for the spectrum integrated over different apertures are summarized in Tables 1 and 2.

In Fig. 2 we show our CO(1–0) spectrum of 3C 326 N integrated over a $5''$ aperture. The blue line shows the Gaussian line fit which gives a $FWHM = 350 \pm 100$ km s⁻¹ and an integrated emission-line flux of $I_{\text{CO}} = 1.0 \pm 0.2$ Jy km s⁻¹ (over a $5''$ aperture, corresponding to the slit width of the IRS spectrum). The observed frequency corresponds to a redshift of $z = 0.0901 \pm 0.0001$ and is similar to the observed redshift of the optical absorption lines within the uncertainties.

2.4. Optical spectroscopy

We complement these new millimeter observations of the cold molecular gas with publicly available optical spectroscopy from the Sloan Digital Sky Survey (York et al. 2000). This spectrum traces the warm ionized gas and the stellar continuum. It has signal-to-noise ratios of ~ 20 – 30 in the continuum (measured

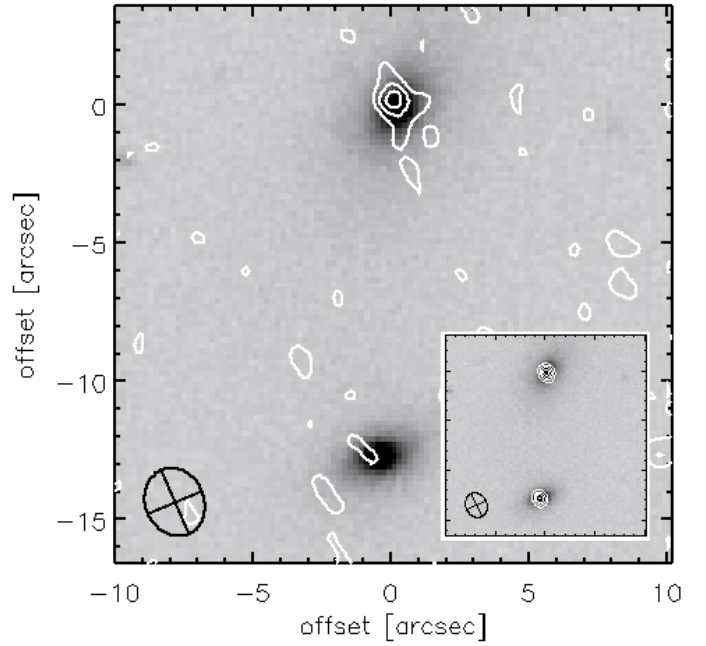


Fig. 1. Continuum-free CO(1–0) emission-line morphology of 3C 326 N (white contours) superimposed on the SDSS *R*-band image of 3C 326 N and 3C 326 S. Contours are given for 3, 4, and 5 σ . The inset shows the same SDSS *R*-band image and the line-free 3 mm continuum morphology superimposed as white contours. The ellipse in the lower left corner shows the beam size and position angle in both images.

Table 1. CO(1–0) line-fit parameters.

Aperture	ν_{obs} [GHz]	Peak [mJy]	Width [km s ⁻¹]
$2.5'' \times 2.1''$	105.744	1.1 ± 0.2	351 ± 98
$5'' \times 5''^a$	105.744	1.5 ± 0.3	351 ± 98

Notes. ^(a) Aperture corresponds to the slit width of the IRS spectrum (solid line in Fig. 2).

at wavelengths around 5000–6000 Å). 3C 326 N is significantly larger than the $3''$ diameter of the SDSS fibers, hence these are near-nuclear spectra including light from the central 5 kpc. This is well matched to the $2.5'' \times 2.1''$ beam size of our IRAM millimeter observations, and to the $5''$ slit width of the Spitzer-IRS spectra. The data cover the spectral range between [OII] $\lambda\lambda 3726, 3729$ and [SII] $\lambda\lambda 6716, 6731$ emission lines and the Ca H+K, Mg b, Na D absorption lines. All lines are relatively broad and spectrally well resolved at the spectral resolving power of the SDSS of $R \sim 1800$ (York et al. 2000). All measured line properties are summarized in Table 3. While the low resolution makes it difficult to resolve certain line doublets, it does allow us to measure velocity dispersions and to analyze the line profiles.

We used the publicly available *Starlight* package (Cid Fernandes et al. 2005) to fit the stellar continuum of 3C 326 N, and to correct our emission-line measurements for the underlying continuum emission and stellar absorption lines. *Starlight* allows to fit the optical stellar continuum of a galaxy with a linear combination of simple stellar populations (SSPs) of different ages and metallicities. We used SSPs from the

Table 2. Intensity of the CO(1–0) emission line after continuum subtraction.

Aperture	redshift	I_{line} [Jy km s ⁻¹]	L' [K km s ⁻¹ pc ²]	F_{cont} [mJy]
2.5'' × 2.1''	0.0901	0.5 ± 0.1	2 ± 1 × 10 ⁸	0.99
5'' × 5'' ^a	0.0901	1.0 ± 0.2	3.8 ± 1 × 10 ⁸	0.99

Notes. ^(a) Aperture corresponds to the slit width of the IRS spectrum.

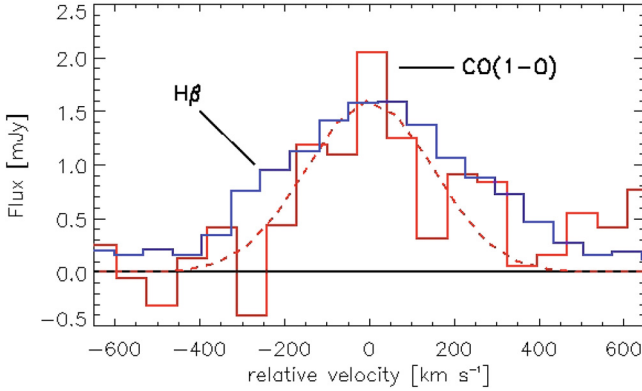


Fig. 2. CO(1–0) millimeter spectrum of 3C 326N (red solid line), and H β line profile (blue solid line). The red dashed line shows our best fit to the CO(1–0) line profile. Both spectra are continuum-subtracted.

stellar population synthesis models of [Bruzual & Charlot \(2003\)](#) for a wide range of ages (from $\sim 10^7$ yrs to several 10^{10} yrs) and metallicities ($Z = 0.0002$ – 0.05). Wavelengths near strong emission lines are excluded from the fit. Formally, we give our best-fit parameters. We find that 97% of the population formed 13 Gyr ago, with the remaining 3% formed 1.3 Gyr ago. However, visual inspection of a fit with or without the intermediate-age population reveals no difference. Only populations with solar or supersolar metallicity contribute. Adopting a Calzetti extinction law we find $A_V = 0.17$ mag. In light of the unavoidable degeneracies and systematic uncertainties, we caution that these fits may be somewhat less constraining than the numerical results suggest at face value. This does not change the basic result, that overall, these fits do imply an old stellar population with age > 10 Gyr, solar metallicity, and low extinction. We show the spectrum of 3C 326 N along with the best fit for the most age-sensitive part around the 4000 Å spectral break in Fig. 7. Unless stated otherwise, we will in the following only refer to the continuum-subtracted emission lines.

2.5. Emission-line kinematics

After subtracting the underlying continuum emission, we fitted the emission lines with Gaussian profiles, where line widths, fluxes, and redshifts are free parameters, except for the [OII] $\lambda\lambda 3726, 3729$; [OIII] $\lambda\lambda 4959, 5007$, [NII] $\lambda\lambda 6548, 6583$, and [SII] $\lambda\lambda 6716, 6731$ doublets, where we required the redshifts and line widths in the two lines of each doublet to be identical. For [OIII] $\lambda\lambda 4959, 5007$, [NII] $\lambda\lambda 6548, 6583$ we also required a flux ratio of 1/3 between the fainter and the brighter component. Results for individual lines are given in Table 3.

All lines have relatively large widths with $FWHM \sim 600$ km s⁻¹. Redshifts and line widths are similar within a scatter of ~ 30 km s⁻¹ for all lines. Redshifts are consistent with the

Table 3. Emission-line fluxes in 3C 326 N.

Line	λ_{rest} [Å]	Redshift	$FWHM^a$ km s ⁻¹	Flux 10 ⁻¹⁵ erg s ⁻¹
[OII]	3727.00	0.09019	623	9.62
H β	4861.30	0.09017	610	2.44
[OIII]	4959.90	0.08991	609	0.58
[OIII]	5006.90	0.09011	609	1.77
[OI]	6300.30	0.09013	612	2.22
[OI]	6363.80	0.09013	612	0.53
[NII]	6548.10	0.09014	601	2.38
H α	6563.30	0.09007	596	9.30
[NII]	6584.10	0.09003	601	7.17
[SII]	6716.40	0.09019	605	4.86
[SII]	6730.80	0.09019	606	3.68

Notes. ^(a) Corrected for instrumental resolution; uncertainties are a few 10 s of km s⁻¹.

systemic redshift of $z = 0.0900 \pm 0.0001$ which we obtained from the stellar absorption lines.

Careful inspection of the profiles of the relatively luminous, and spectrally well isolated [OIII] $\lambda\lambda 4959, 5007$ and [OI] $\lambda\lambda 6300, 6363$ lines reveals the presence of very broad components with widths of $FWHM = 1635$ km s⁻¹ (Fig. 4). Broad components of forbidden lines are not associated with typical nuclear broad-line regions ([Sulentic et al. 2000](#)) but do suggest that some of the ISM in 3C 326 N is kinematically strongly disturbed. The redshifts and line width of the very broad components are overall consistent with the wind component of the Na D line discussed in Sect. 5. Equally large line widths of ionized gas have also been found by [Holt et al. \(2008\)](#) in nearby radio galaxies showing the signs of AGN feedback and by [Nesvadba et al. \(2006, 2007, 2008\)](#) in the kpc-scaled jet-driven outflows of ionized gas in high-redshift radio galaxies.

To compensate for the difficulty of fitting broad components at relatively low signal-to-noise ratios with more narrow, superimposed components, we required that all four lines have the same redshift and line widths, which yields reasonably good residuals. For the broad lines, we do not find a significant blueshift or redshift relative to the narrow components.

Due to the large line widths, several lines are blended, which makes a detailed fit more difficult (namely, these are [OII] $\lambda\lambda 3726, 3729$, H α and [NII] $\lambda\lambda 6548, 6583$, and [SII] $\lambda\lambda 6716, 6731$). We did not attempt to fit multiple components to these lines.

2.6. Characteristics of the Na D lines

Figure 5 shows the strong and broad Na D absorption feature that we detect in our SDSS spectrum of 3C 326 N. We used the stellar population synthesis models described in Sect. 2.4 to estimate and remove the stellar component of the Na D line which can be significant in stellar populations. We also show Mg b in Fig. 5, which is purely stellar and illustrates the accuracy of the population synthesis fit.

Figure 5 shows that the Na D lines in 3C 326 N are very broad, so that we cannot directly measure the equivalent width of each component of the Na D doublet. We therefore modeled the lines using the atomic data compiled in [Morton \(1991\)](#), allowing for changes in the turbulent velocity, velocity offsets, and covering fraction. Since we do not resolve individually the lines of the doublet, covering fraction (C_f) and optical depth are degenerate unless the line shapes are accurately known. The lines

Table 4. Measured emission-line ratios in 3C 326 N and expected ratios for a pure-shock model and a model assuming a shock and precursor (Allen et al. 2008).

Line ratio	Observed	Shock	Shock and precursor
H β /H α	0.26	0.33	0.33
[OIII]/H β	0.72	0.82	1.48
[OI]/H α	0.24	0.22	0.13
[NII] λ 6584/H α	0.77	0.68	0.47
[SII]/H α	0.61	0.52	0.32
[SII] $\lambda\lambda$ 6716,6731	1.32	1.23	1.24
[NeII](12.81 μ m)/H α	0.46	0.45	0.28
[NeII](12.81 μ m)/[NeIII](15.6 μ m) ^(a)	>1.8	2.2	0.73

Notes. ^(a) [NeII] and [NeIII] fluxes are taken from Ogle et al. (2010).

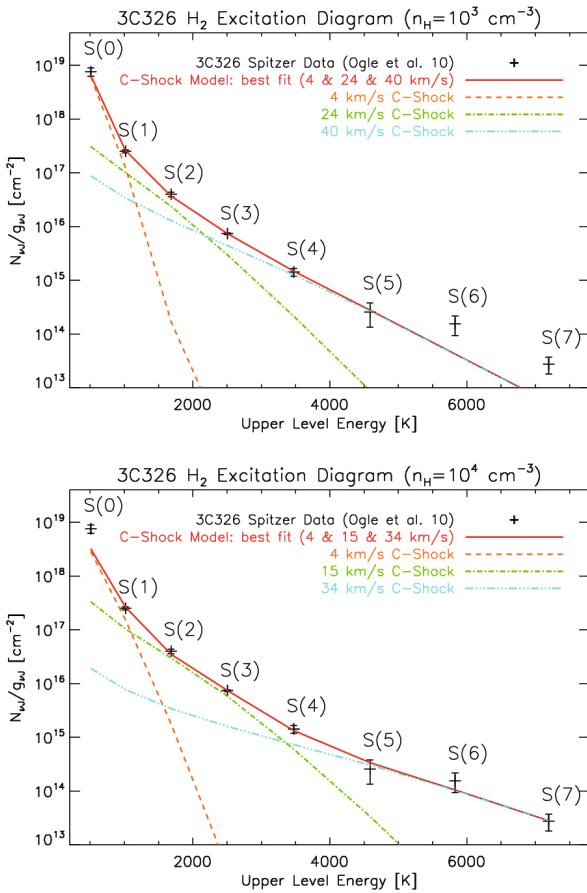


Fig. 3. Observed H₂ excitation diagrams for 3C 326 (1 σ error bars) and model results of magnetic shocks (see Guillard et al. 2009, for details), for pre-shock densities of $n_H = 10^3$ (upper panel) and 10^4 cm⁻³ (lower panel). Dashed lines show the contribution of each C-shock velocity to the best-fit model. The red line shows the combination of these 3 shocks.

are heavily blended and of insufficient S/N to have confidence in the line shapes.

We find that the Na D lines are heavily saturated so that we can only give lower limits on the Na I column densities. Values in the range $4\text{--}10 \times 10^{14}$ cm⁻² (for $C_f = 1$ and 0.5 respectively) are most likely. The Doppler parameter of the doublet is ~ 800 km s⁻¹ with a most probable velocity offset of about -350 km s⁻¹ relative to the systemic redshift. For the highest column densities, corresponding to a covering fraction $C_f < 0.5$, the line profile begins to show a “flat core”, which is

not favored by the data. Therefore, it appears that the best fitting models favor a relatively high covering fraction. We note that the best fit Doppler parameter and velocity offset are not very sensitive to the range of columns and covering fractions explored. We will further explore the wind properties in Sect. 5.1.

3. The origin of the line emission

The line emission of interstellar gas can be powered by a number of different astrophysical processes like energetic photons from starbursts and AGN, cosmic rays, or mechanical energy injected into the ISM by stars, AGN, or various dynamical processes. We will now analyze the emission lines of the molecular and ionized gas in 3C 326 N to identify the physical mechanism that is giving rise to the luminous line emission in this galaxy.

3.1. Molecular emission-line diagnostics

Emission-line ratios in the optical are a popular tool to investigate the heating mechanism of the ionized gas (e.g., Baldwin et al. 1981; Veilleux & Osterbrock 1987), and to differentiate between star-forming galaxies and AGN. Somewhat in analogy we will now construct a molecular diagnostic diagram based on the CO(1–0), pure-rotational H₂ and PAH emission shown in Fig. 6. We start with a short discussion of the astrophysical origin of each tracer before presenting the resulting diagram.

Critical densities for the S(0) to S(3) lines are moderate (10 to 10^4 cm⁻³ in molecular gas at 500 K; Le Boulbot et al. 1999), so that the lowest rotational states of H₂ are populated by collisions rather than fluorescence. The first rotational lines of H₂ are therefore dominant cooling lines for molecular gas over a wide temperature range of $\sim 10^2\text{--}10^3$ K. They measure the power dissipated by all heating processes of the warm molecular gas ($T > 100$ K). This includes UV or X-ray photons produced by young stars in photon or X-ray dominated regions, or the dissipation of mechanical energy as proposed by Guillard et al. (2009) for Stephan’s Quintet. Ferland et al. (2008) proposed that cosmic rays could be the dominant energy source powering the extended warm intracluster H₂ line in the Perseus galaxy cluster. The CO(1–0) emission-line luminosity is associated with the cold molecular phase, to the extent where it is commonly used to estimate the cold molecular gas mass (e.g., Solomon et al. 1997). Thus, if the gas traced by CO and H₂ is physically associated, then the H₂ to CO(1–0) ratio is a measure of the total heating of the molecular gas per unit molecular gas mass.

PAH emission in star-forming regions is found along the surfaces of molecular clouds heated by UV photons, but not within HII regions, where PAHs are destroyed

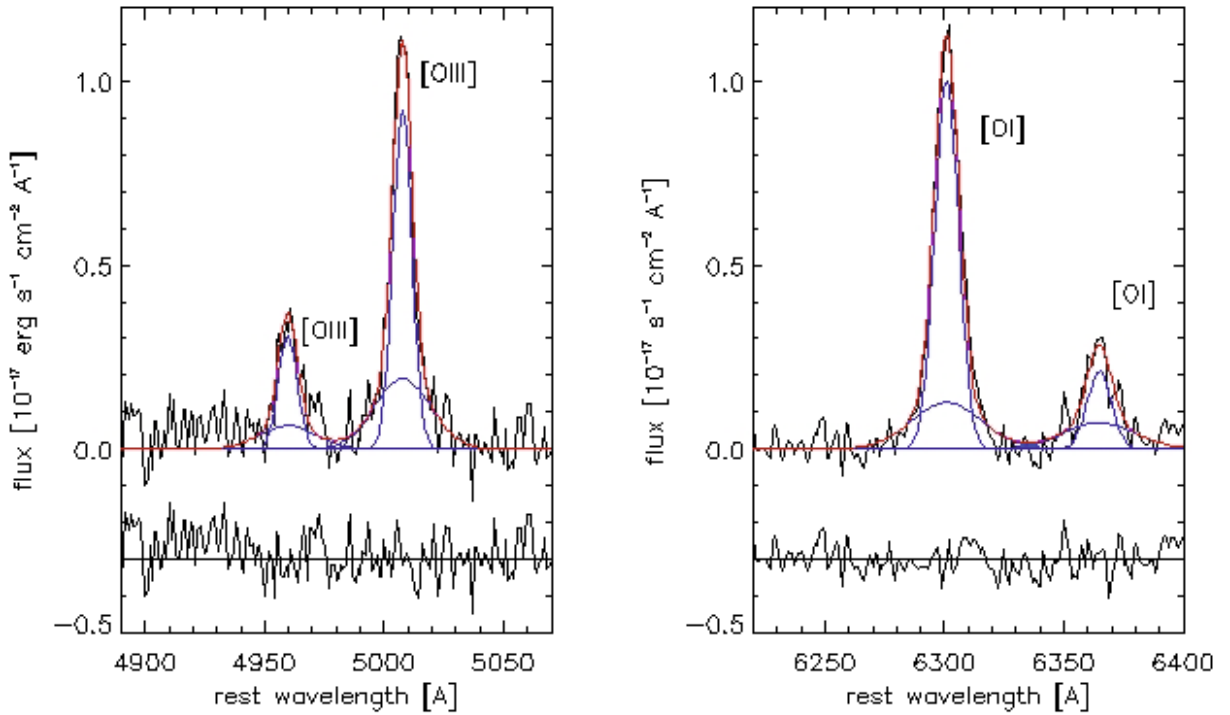


Fig. 4. Multiple-component fits to the [OIII] $\lambda\lambda$ 4959,5007 and [OI] $\lambda\lambda$ 6300,6363 line emission in 3C 326 N. The broad component is best seen in the [OIII] λ 5007 emission line. We assumed the same redshifts and line widths for all lines.

(e.g. Cesarsky et al. 1996; Tacconi-Garman et al. 2005). In addition, on galactic scales, some of the PAH emission may originate from the diffuse interstellar medium rather than star-forming regions, as argued by Draine et al. (2007) based on the modeling of the dust emission of SINGS galaxies. In either case the PAH emission is powered by UV photons. Thus, we can use the ratio of PAH to H₂ emission as an empirical measure for the contribution of UV photons to the total H₂ heating. This is supported by the tight correlation between the 7.7 μ m PAH feature and H₂ luminosity found in star-forming regions (Rigopoulou et al. 2002; Roussel et al. 2007).

In Fig. 6 we combine both line ratios into one diagnostic diagram. We also include the position of 3C 326 N, Stephan's Quintet (SQ), and of several H₂-luminous radio galaxies from the sample of Ogle et al. (2010) which have published CO measurements. We exclude central galaxies in cooling-flow clusters where CO line emission is extended over sizes much greater than the IRS slit. We also show star-forming galaxies and AGN from the SINGS survey, taken from Roussel et al. (2007). To convert 8 μ m flux densities into PAH 7.7 μ m luminosities, we used the prescription of Roussel et al. (2007). We used the starburst template of Brandl et al. (2006) to bring the integrated PAH fluxes of the radio galaxies measured by Ogle et al. (2010) on the same scale. In Fig. 6, 3C 326 N and the SQ shock are the most extreme representants of H₂ luminous galaxies with the highest ratio of H₂-to-PAH emission and H₂-to-CO emission.

3.2. What powers the H₂ emission?

3.2.1. Energetic photons

We will now use our molecular emission-line diagnostics to show that UV photons produced in PDRs cannot make a major contribution to heating the molecular gas in 3C 326 N.

In the diagnostic diagram shown in Fig. 6, black lines mark the line ratios derived for PDR models to illustrate in which parts of the diagram the H₂ heating is dominated by UV photons. The H₂ line emission in PDRs is derived from the calculations of Kaufman et al. (2006). The total extinction of the PDR models is $A_V = 10$ mag, large enough to ensure that most of the incident UV light is being absorbed. For the PAH emission, we assumed that $\nu I_{\nu,8} = 0.16 \times F_{IR}$, where F_{IR} is the bolometric infrared flux, and $I_{\nu,8}$ the flux density at 8 μ m. This conversion factor corresponds to the models of Draine & Li (2007) for a PAH-to-dust mass fraction $q_{PAH} = 3.55\%$ Draine & Li (2007), the median value for galaxies with Galactic metallicity in the SINGS sample (Draine et al. 2007).

The star-forming galaxies from SINGS are our control sample with “ordinary” line emission. They fall into the portion of the diagram spanned by the PDR models, as expected if most of their molecular line emission is powered by star formation. Their positions in the diagram suggest a ratio between the intensity of the UV field and the gas density of about 0.1 to 1 cm⁻³, and a UV intensity several times higher than that in the solar neighborhood.

In galaxies which do not fall into the portion of the diagram spanned by the PDR models, the molecular gas is heated by another mechanism than photons produced in star-forming regions. This includes 3C 326 N, 3C 424, and the intergalactic shock in Stephan's Quintet as the most extreme cases, as well as several other H₂ luminous radio galaxies. Similarly, about half of the SINGS AGN fall into this region, albeit not at its extreme end.

For the sake of completeness, we should note that X-ray heating seems also unlikely to explain the H₂ line emission in the SINGS AGN (Roussel et al. 2007). Similarly, Ogle et al. (2010) find that the observed X-ray luminosities of their sample of H₂ luminous radio galaxies are not sufficient to power the H₂ line emission.

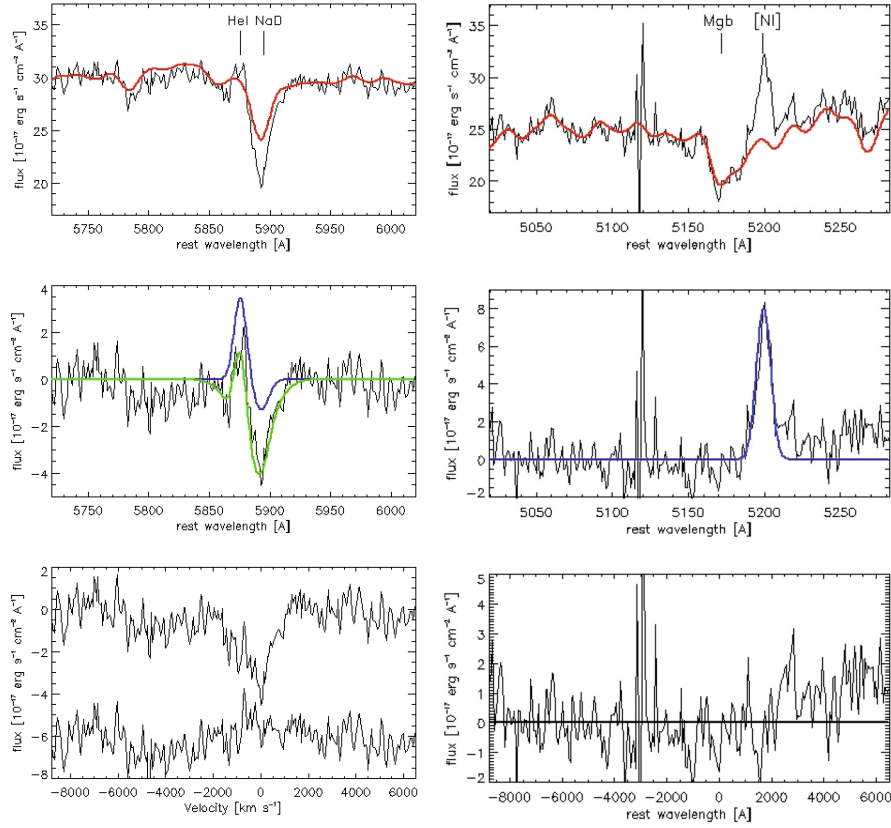


Fig. 5. *left:* NaD absorption line in 3C 326 N. *Upper panel:* the black line shows the spectrum, and the red line the spectral energy distribution of the best-fit stellar population. *Mid panel:* the same spectrum with the best-fit stellar continuum subtracted. The green line marks our absorption line fit with HeI λ 5876, and two Gaussian NaD components, one at the systemic velocity, another one with an offset of -350 km s $^{-1}$ representing the blue wing. The blue line shows the HeI line and the stellar NaD component. *Lower panel:* the same spectrum with the stellar continuum and the HeI emission-line subtracted (*upper spectrum*). The lower line shows the residual after subtraction of HeI, the stellar component, and the NaD absorption line. The residual spectrum is shifted by an arbitrary amount along the ordinate. The abscissa gives the velocity offsets relative to a systemic redshift of $z = 0.090$. *right:* the same for Mg b, a line which does not have a strong interstellar component.

3.2.2. Cosmic rays

Ferland et al. (2008) recently proposed that heating by cosmic rays may explain the extended, filamentary emission of warm molecular hydrogen in massive galaxy clusters experiencing episodes of AGN feedback from their massive central galaxy. We discuss this excitation mechanism based on an approach that is broadly similar to that of Ogle et al. (2010)

The critical density of the S(0) and S(1) lines is sufficiently low (Le Bourlot et al. 1999) to allow us to safely assume that the $J = 2$ and 3 levels of H₂ are thermalized by collisions. The S(0) and S(1) line fluxes in Ogle et al. (2010) correspond to an emission-line luminosity of 1.9×10^{41} erg s $^{-1}$. Dividing this luminosity by the H₂ mass of $9.5 \times 10^8 M_{\odot}$ from Ogle et al. (2010), we can estimate a cooling rate through the H₂ S(0) and S(1) lines of 3.4×10^{-25} erg s $^{-1}$ H₂ $^{-1}$. Including the S(2) and S(3) lines increases this luminosity to 9×10^{-25} erg s $^{-1}$ H₂ $^{-1}$. What ionization rate from cosmic rays would be required to provide the corresponding amount of heat?

Gas heating associated with the ionization of H₂ by cosmic rays is ~ 12 eV per ionization, including the contribution from H₃ $^{+}$ recombination and H₂ re-formation (e.g. Le Petit et al. 2006). To balance line cooling, the ionization rate per H₂, ζ_{H_2} , must be few $\times 10^{-14}$ s $^{-1}$. For such a rate, cosmic rays are the main destruction path of H₂ molecules. The molecular gas fraction depends on the rate of ionization and gas density $\zeta_{\text{H}_2}/n_{\text{H}_2}$, and the

gas is molecular for $n_{\text{H}} > 10^4$ cm $^{-3}$ (see Fig. 2 of Ferland et al. 2008). At such densities, the H₂ rotational states are thermalized up to $J \geq 5$, and the higher- J lines up to S(3) are also cooling lines. Dividing the H₂ S(0)–S(3) luminosity by the energy released per ionization, we estimate the required ionization rate, $\zeta_{\text{H}_2} \sim 5 \times 10^{-14}$ s $^{-1}$. This value is larger than what is inferred from H₃ $^{+}$ observations in the Milky Way, by a factor 100 for the diffuse interstellar medium (Indriolo et al. 2007), and by more than a factor 10 for the molecular gas within 200 pc from the Galactic center (Goto et al. 2008). It is therefore unlikely that the warm molecular gas in 3C 326 N is powered by cosmic rays.

3.2.3. Mechanical heating through shocks

Having ruled out UV and X-ray photons as a possible mechanism to power the line emission in 3C 326 N, and having shown that cosmic rays are unlikely, our best remaining candidate is mechanical heating through shocks. This is in close analogy to the model of Guillard et al. (2009) who studied the intergalactic shock in Stephan’s Quintet, and found that the H₂ line emission is powered by the dissipation of kinetic energy injected by the interaction of two galaxies. 3C 326 N and Stephan’s Quintet fall into similar regions of our diagnostic diagram (Fig. 6), suggesting their line emission is powered by a similar physical mechanism. In Sects. 4 and 6 we will demonstrate that the radio source is the only viable energy source which can explain all of the

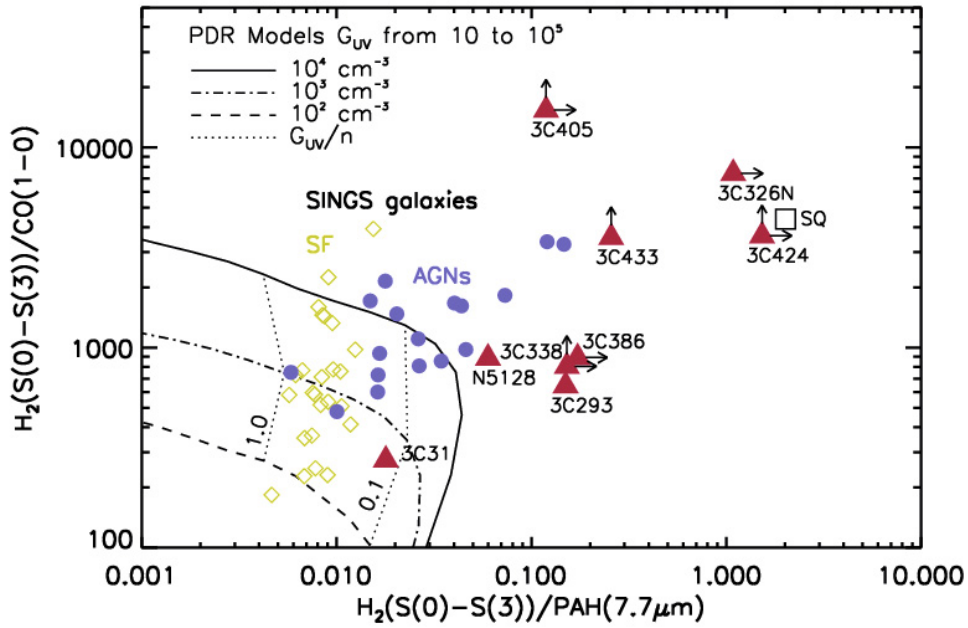


Fig. 6. Molecular diagnostic diagram to distinguish between AGN and star formation. Lines mark PDR models with various assumptions for the UV radiation fields. Small blue circles and yellow diamonds: star-forming galaxies and AGN from the SINGS survey, respectively (measurements are taken from Roussel et al. 2007). Red triangles: H_2 luminous radio galaxies (H_2 and PAH fluxes are taken from Ogle et al. 2010). Black empty square: Stephan’s Quintet (taken from Guillard et al. 2009).

phenomenology observed in 3C 326 N, and present a physical framework through which the energy injection by the radio source and the molecular line emission can be related.

3.3. What powers the optical line emission?

In the previous section we presented new, “molecular” diagnostics to argue that the luminous H_2 emission in 3C 326 N (as well as other H_2 radio galaxies) may be powered by the dissipation of mechanical energy in the interstellar medium of the host galaxy. It may be illustrative to use our SDSS spectra to compare this result with the optical diagnostics.

Table 3 lists the fluxes measured for various optical emission lines in 3C 326 N. Comparison with the classical BPT-diagrams (Baldwin et al. 1981; Veilleux & Osterbrock 1987; Kewley et al. 2006) shows that 3C 326 N falls within the LINER (Heckman 1980) part of the diagrams, similar to most H_2 luminous radio galaxies of Ogle et al. (2010) and also the galaxy-wide shock in Stephan’s Quintet (Xu et al. 2003).

The excitation mechanism of the atomic lines in LINERs is a long-standing issue in the literature where some studies favor photo-ionization by the AGN (e.g., Veilleux & Osterbrock 1987) while other studies propose shock excitation (e.g., Clark et al. 1998; Dopita et al. 1997; Monreal-Ibero et al. 2006). Dopita & Sutherland (1995, 1996) show that the spectral characteristics of LINERs can be modeled with excitation from fast, radiative shocks without the emission from the radiative precursor of the shock. The radiative precursor of a fast shock moving into low-density gas adds an emission component which has the spectral characteristics of photoionized gas with a high ionization parameter. However, the line ratios in 3C 326 N, in particular the ratio between the [NeII]/[NeIII] lines in the mid-infrared, suggest a low ionization parameter. This apparent contradiction can be resolved if a clumpy or filamentary gas distribution enhances the

“leaking” of hard photons along sight lines where the photons can escape without interacting with the pre-shock gas. As in the shock of Stephan’s Quintet, most of the gas in 3C 326 N is in H_2 at densities $n_H > 10^3 \text{ cm}^{-3}$ much higher than the density of the ionized gas (Guillard et al. 2009), in good agreement with this scenario.

Quantitatively, using the models of Allen et al. (2008) for 3C 326 N, we find that the ratios between the main optical lines in Table 3 are close to those of a 250 km s^{-1} shock moving into ionized gas with a 1 cm^{-3} preshock density and a low magnetic parameter, $B/\sqrt{n} < 1 \mu\text{G cm}^{-3/2}$. Observed and modelled line ratios are compared in Table 4. This is not a unique solution, in particular, the line ratios are also compatible with lower densities for similar shock velocities. A detailed analysis of the alternative models (and model parameters, as done in Dopita et al. 1997) for the interaction between radio jet and interstellar medium in M 87 is beyond the scope of this paper.

We will merely use these models to determine the bolometric luminosity of the ionized gas from the observed $H\beta$ luminosity. Using the output of Allen et al. (2008) for shock velocities below about 300 km s^{-1} we can calculate the ratio of $H\beta$ luminosity, $\mathcal{L}_{H\beta}$, to the total luminosity produced by the shock. We find that $\mathcal{L}_s \sim 200 \pm 50 \mathcal{L}_{H\beta}$. This bolometric correction is slightly larger for magnetic parameters below the equipartition value. This large correction factor is due to the much larger brightness of the UV emission lines relative to the optical line emission, which we did not observe. With the measured $H\beta$ flux and using this model at face value, we find $\mathcal{L}_s \sim 1 \times 10^{43} \text{ erg s}^{-1}$, a factor ~ 10 more than the total H_2 line luminosity in the S(0)–S(7) rotational lines (Ogle et al. 2010). This corresponds to the isobaric cooling of gas at temperatures of $\sim 10^6 \text{ K}$ for a mass flow of order of a few $100 M_\odot \text{ yr}^{-1}$. This mass flow is very large, and we will discuss in Sect. 6.3 how this result may be interpreted as a repeated mass cycling between gas phases driven by interactions

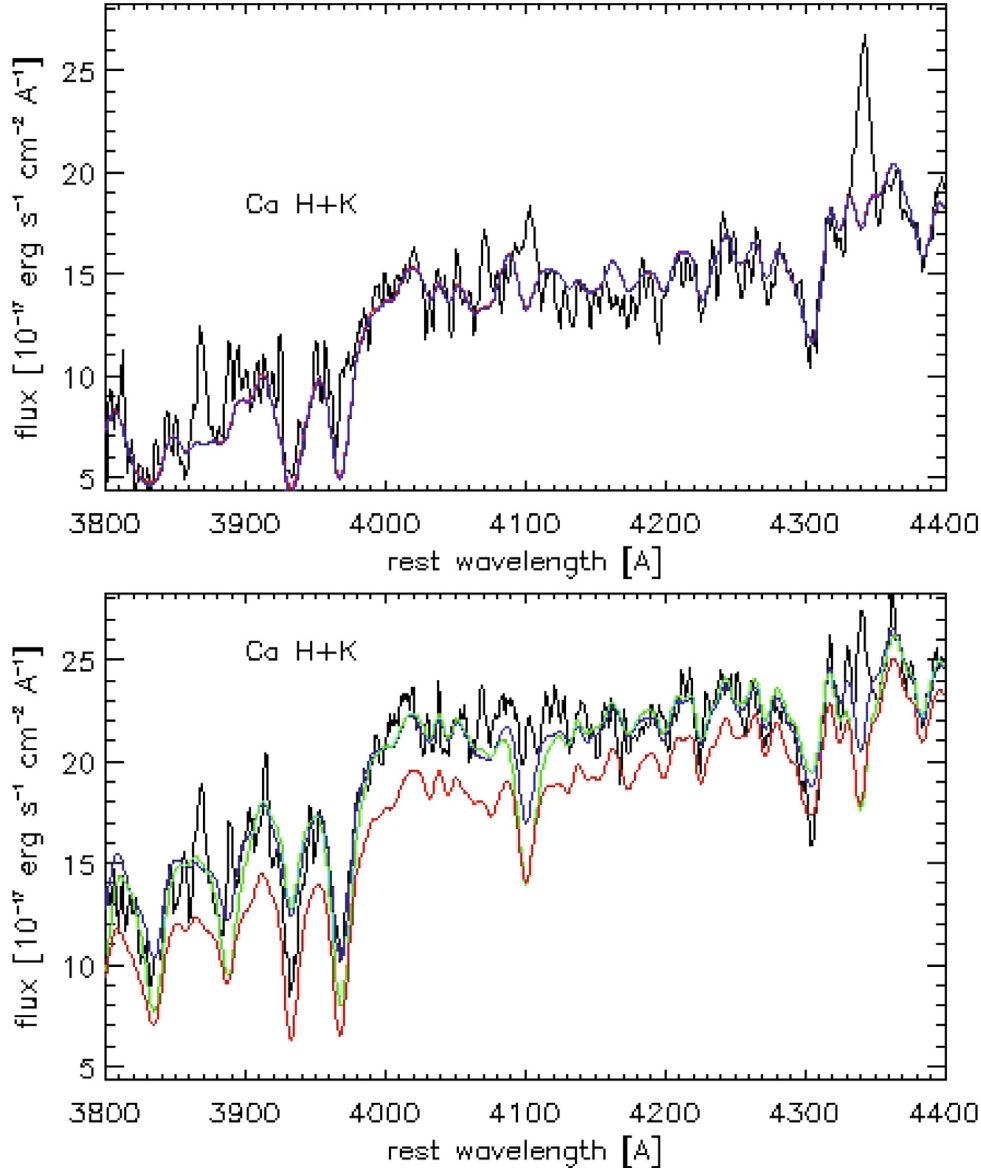


Fig. 7. Wavelengths near the 4000 Å break, which are most sensitive to the star-formation history of 3C 326 N (*upper panel*) and 3C 293 (*lower panel*). The black line marks the SDSS spectrum in each panel. Red, blue, and green lines mark the *Starlight* spectral fits for different star-formation histories, see Sect. 8.1 for details. *Upper Panel:* red – Stellar population older than 10^{10} yr. Blue – Old and intermediate-age (few 10^9 yrs) stellar population. *Lower Panel:* red – Stellar population older than 10^{10} yr. Green – Old and intermediate-age (few 10^{8-9} yr) population. Blue – Old, intermediate-age, and young (10^7 yr) stellar population.

between the radio jet and the multiphase interstellar medium of the host. Obviously, due to the uncertainties in the measurement and modeling all of these values have uncertainties of factors of a few.

It is well possible that not all of the optical line emission is excited mechanically. The dynamical interaction between gas phases must include turbulent mixing between the cold and hot gas, which produces extreme UV radiation along the surfaces of cold clouds. This radiation is an additional, and maybe significant, source of ionization powered by the thermal energy of the cocoon. Crawford & Fabian (1992) show that this mechanism could account for parts of the line emission in ionized gas in cooling flows, consistent with observed line ratios. In this case, the bolometric correction with respect to H β depends on the effective temperature of the gas after mixing and could be significantly smaller. With regard of this uncertainty on the radiative excitation, we will in the following adopt a fiducial value of

1×10^{43} erg s⁻¹. Again, the uncertainties of this estimate are likely factors of a few.

3.4. Photoionization by stars and the AGN

In the above estimates we assumed that all of the optical line emission is due to shocks, and that other processes like photoionization from star formation or the AGN can be neglected. With the low star-formation rate and faint AGN X-ray emission from 3C 326 N this galaxy is ideally suited to set stringent limits on the contribution of these processes to the observed line emission. For example, the observed star-formation rate of $\leq 0.07 M_{\odot} \text{ yr}^{-1}$ would imply an H α luminosity $\mathcal{L}(\text{H}\alpha) \sim 1 \times 10^{40}$ erg s⁻¹ (corresponding to a H β luminosity of few $\times 10^{39}$ erg s⁻¹) for a continuous star-formation history and using the models of Bruzual & Charlot (2003). This corresponds to $\sim 5\%$ of the measured H α luminosity of 3C 326 N.

Table 5. Observed and bolometric luminosity of the line emission of molecular and ionized gas (H α).

	Molecular Gas	Ionized gas	Radio source ^a	AGN X-ray ^b
$\log \mathcal{L}_{\text{obs}}^c$	41.9	41.3	44.6	40.6
$\log \mathcal{L}_{\text{bol}}^d$	42.0	43		
$\log E_{\text{kinetic}}^e$	57.5	55.7	59.8	
$\log \text{Mass}^f$	9.5	7.3		
$\log \tau_{\text{diss}}^g$	8.2 ^h	7.2 ⁱ		

Notes. ^(a) Radio luminosity measured at 327 MHz. ^(b) X-ray luminosity of the nuclear point source from [Ogle et al. \(2010\)](#). ^(c) erg s⁻¹. ^(d) erg s⁻¹. ^(e) erg. ^(f) M_{\odot} . ^(g) yrs. ^(h) For dissipation through the molecular gas. ⁽ⁱ⁾ Assuming that all of the UV/optical line emission is due to dissipation of kinetic energy.

We can also rule out a dominant role of the AGN in photoionizing the gas, for the simple reason that the [OIII] λ 5007 luminosity alone exceeds the luminosity emitted in the X-ray. [Ogle et al. \(2010\)](#) find an X-ray luminosity of 4×10^{40} erg s⁻¹ for 3C 326 N, whereas our [OIII] λ 5007 measurements indicate an [OIII] λ 5007 luminosity of $\log \mathcal{L}_{\text{[OIII]}\lambda 5007} = 7 \times 10^{40}$ erg s⁻¹ (including the extinction correction of a factor 2). [Heckman et al. \(2004\)](#) find that the bolometric luminosity of quasars scales with [OIII] λ 5007 emission-line luminosity as $\mathcal{L}_{\text{bol}} \sim 3500 \mathcal{L}_{\text{[OIII]}\lambda 5007}$. For 3C 326 N the observed [OIII] λ 5007 flux implies a bolometric luminosity of few $\times 10^{44}$ erg s⁻¹, three orders of magnitude greater than that estimated from the X-ray measurement. This indicates that the AGN photoionization is unlikely to be the dominant mechanism in exciting the optical line emission in 3C 326 N.

4. Mass and energy budgets

The relative mass budgets of warm and cold molecular gas and the warm ionized gas provide important constraints on the physical and astrophysical conditions of a galaxy. By “physical conditions” we refer to the gas properties, which relate directly to the observations. By “astrophysical conditions” we refer to the galaxy properties and the mechanism which is causing the observed gas properties. Typically, in gas-rich, actively star-forming galaxies the amount of cold molecular gas exceeds the masses of warm molecular and ionized gas by factors 10–100 (see [Roussel et al. 2007](#); [Higdon et al. 2006](#), for samples of nearby galaxies and ULIRGs, respectively). We will now show that this ratio is much smaller for 3C 326 N. All masses, luminosities, and kinetic energies are summarized in Table 5.

4.1. Molecular gas mass

4.1.1. Direct estimate of the luminosity and mass of warm molecular gas

The mass of warm molecular gas in 3C 326 has been estimated by [Ogle et al. \(2007, 2010\)](#) by fitting the H₂ S(0) to S(7) rotational line fluxes with 2 or 3 components at different temperatures where H₂ excitation and ortho-to-para ratios are assumed to be thermalized. This yields a mass of $1.0 \times 10^9 M_{\odot}$.

In the present analysis, we associate the H₂ emission with the dissipation of kinetic energy in the molecular gas. Therefore we follow a different approach to estimate the mass and luminosity of warm molecular gas. As in [Guillard et al. \(2009\)](#), we model the dissipation process with magnetic shocks in molecular gas, which maximizes the H₂ luminosity per total emitted power. In this sense, our results represent a lower limit to the dissipated energy required to account for the observed H₂ luminosity.

Each shock model includes a range of gas temperatures which depend on the shock velocity, pre-shock gas density and intensity of the magnetic field. We use the grid of models presented by [Guillard et al. \(2009\)](#) for proton densities of $n_{\text{H}} = 10^3 \text{ cm}^{-3}$ and 10^4 cm^{-3} , respectively, an initial ortho-to-para ratio of 3 and a magnetic parameter, $B/\sqrt{n_{\text{H}}} = 1 \mu\text{G cm}^{-3/2}$.

The shock velocity is the only parameter that we allow to vary. A combination of three shocks is required to match the emission in all 8 H₂ lines, S(0) to S(7). These fits provide a scaling factor for each of the three shocks which represents a mass flow, the amount of gas traversing the shocks per unit time. As discussed in [Guillard et al. \(2009\)](#), this fit is not unique but the proposed solution may be used to quantify the relevant range of shock velocities, and to estimate the warm gas masses by multiplying the mass flows with the gas cooling time, and the shock luminosities by integrating over all cooling lines.

Excitation diagrams for models with two different gas densities, 10^3 cm^{-3} and 10^4 cm^{-3} , respectively, are shown in Fig. 3. The corresponding H₂ line fluxes are listed in Table 6. They are smaller than the kinetic energy fluxes one may compute from the mass flow and shock velocity because some of the energy is transferred to the magnetic field. The luminosities of the mid-infrared H₂ lines are close to the bolometric values obtained by integrating the emission in all lines because the H₂ rotational lines are the main cooling lines of magnetic shocks. Summing over the three shocks we estimate a total luminosity of $10^{42} \text{ erg s}^{-1}$ for the molecular Hydrogen.

Table 7 lists the gas cooling times and H₂ masses down to temperatures of $T = 150 \text{ K}$ for each of these models. The total mass we obtain for gas at temperatures larger than $T = 150 \text{ K}$, $1.3\text{--}2.7 \times 10^9 M_{\odot}$, is slightly larger than that derived by [Ogle et al. \(2010\)](#), and we will in the following assume a fiducial molecular gas mass of $2 \times 10^9 M_{\odot}$. The small difference between the estimates of [Ogle et al. \(2010\)](#) and our results is due to different ortho-to-para ratios and moreover, in our lowest-density models, the S(0) and S(1) lines are not fully thermalized.

4.1.2. CO(1–0) luminosity and total molecular gas mass

The CO emission-line luminosity is often used as an empirical measure of the mass of cold molecular gas. In Sect. 2.3 we estimated an integrated CO(1–0) emission-line flux of $I_{\text{CO}} = 1.0 \pm 0.2 \text{ Jy km s}^{-1}$ from our millimeter spectroscopy at the IRAM Plateau de Bure Interferometer, extracted from a 5'' aperture. Using Eq. (3) of [Solomon et al. \(1997\)](#) we translate this value into a CO(1–0) emission-line luminosity of $L'_{\text{CO}} = 3.8 \times 10^8 \text{ K km s}^{-1} \text{ pc}^2$ at a redshift of $z = 0.090$. Applying a Galactic H₂-to-CO conversion factor of $4.6 M_{\odot}/(\text{K km s}^{-1} \text{ pc}^2)$ as determined for gas in the molecular ring of the Milky Way ([Solomon et al. 1992](#)), this would correspond to a mass of cold

Table 6. MHD shock model parameters and predicted H₂ line fluxes^a for 3C 326.

n_{H}^b [cm ⁻³]	V_s^c [km s ⁻¹]	H ₂ line fluxes [10 ⁻¹⁸ W m ⁻²]								$\mathcal{F}_{\text{H}_2}^d$	$\mathcal{F}_{\text{bol}}^e$
		S(0)	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)	S(7)		
10 ⁴	4	0.74	4.51	0.18	6.1×10^{-3}	3×10^{-4}	8.6×10^{-4}	2.9×10^{-4}	7.5×10^{-4}	5.43	13.02
	15	0.09	3.22	3.19	10.36	1.35	0.68	0.02	2.2×10^{-3}	18.92	20.55
	34	4.2×10^{-3}	0.19	0.29	2.32	1.38	5.33	1.58	2.99	14.09	16.35
	Sum	0.84	7.92	3.66	12.69	2.73	6.01	1.60	2.99	38.44	49.92
10 ³	4	1.61	3.74	0.018	1.3×10^{-3}	4.3×10^{-4}	1.2×10^{-3}	4×10^{-4}	10 ⁻³	5.37	10.6
	24	0.08	3.01	2.44	5.09	0.46	0.17	7×10^{-3}	6.6×10^{-3}	11.3	11.6
	40	0.02	1.01	1.32	7.57	2.73	5.24	0.68	0.56	19.13	20.07
	Sum	1.71	7.75	3.78	12.66	3.2	5.42	0.68	0.56	35.77	42.27
Spitzer Obs.		2.0 ± 0.3	7.5 ± 0.5	4.1 ± 0.4	12.6 ± 0.4	3.1 ± 0.6	5.0 ± 2.5	2.5 ± 1.0	2.9 ± 1.0	39.7 ± 2.3	

Notes. ^(a) This table lists the shock model velocities, the predicted H₂ rotational line fluxes, and bolometric luminosities associated with each shock velocity components. Measured H₂ fluxes are taken from Ogle et al. (2007, 2010). ^(b) Preshock hydrogen density. ^(c) MHD shock velocity. ^(d) Sum of the H₂ S(0) to S(7) rotational lines in 10⁻¹⁸ W m⁻². ^(e) Sum over all the lines (bolometric luminosity of the shock).

Table 7. MHD shock model parameters, mass flows and cooling times.

n_{H}^a [cm ⁻³]	V_s^b [km s ⁻¹]	Mass flow [M_{\odot} yr ⁻¹]	t_{cool}^c [yrs]	M_{gas} [M_{\odot}]
10 ⁴	4	70 100	19 050	1.3×10^9
10 ⁴	15	5950	3320	2.0×10^7
10 ⁴	34	730	1000	7.3×10^5
10 ³	4	41 050	65 000	2.7×10^9
10 ³	24	1100	11 500	1.3×10^7
10 ³	40	630	5400	3.4×10^6

Notes. ^(a) Pre-shock density.

^(b) MHD shock velocity.

^(c) Cooling time.

molecular gas of $M_{\text{cold}}^{326\text{ N}} = 1.5 \times 10^9 M_{\odot}$. We will further discuss the appropriateness of this H₂ conversion and related uncertainties in Sect. 7.

Comparison with Sect. 4.1.1 shows that the amount of warm molecular gas measured directly from the mid-infrared lines is similar to the H₂ molecular mass inferred from the CO(1–0) flux estimated from our PdBI observations. This is a highly unusual finding compared to star-forming galaxies where the ratio of warm to cold molecular gas mass is of order 10⁻¹ to 10⁻² (Roussel et al. 2007; Higdon et al. 2006) for the same CO-to-H₂ conversion factor. However, it is not very different from the ratio of ~0.3 found in molecular clouds near the Galactic center (Rodríguez-Fernández et al. 2001).

The Galactic center may be an adequate nearby analog for the properties of the molecular gas in 3C 326 N. In the Galactic center cold dust temperatures indicate that the gas cannot be heated by UV photons (Lis et al. 2001), but possibly by shocks or cosmic rays (Rodríguez-Fernández et al. 2001; Yusef-Zadeh et al. 2007). The H₃⁺ observations presented by Goto et al. (2008) imply an H₂ ionization rate lower than the value required to account for the temperature of the warm molecular gas of ~150 K (Rodríguez-Fernández et al. 2001) with heating by cosmic rays, $\zeta_{\text{H}_2} \sim 10^{-13} \text{ s}^{-1}$ (Yusef-Zadeh et al. 2007).

From detailed studies of several molecular species in the Galactic center, Lis et al. (2001); Huettnermeister et al. (1998) conclude that all of the molecular gas in this environment may be warm at temperatures above $T = 50$ K. By analogy we caution that the usual distinction between cold and warm gas

measured through CO line emission and infrared H₂ lines, respectively may not apply to 3C 326 N. Most of the CO line emission in 3C 326 N could in fact be associated with the warm gas. Observations of higher- J transitions are necessary to test this hypothesis. We used the RADEX LVG code (van der Tak et al. 2007) to verify that the intensity of the CO(1–0) line is relatively insensitive to the gas temperature for a given CO column density. For example, in a temperature range of 10–100 K, the intensity changes by about a factor 2 (see also Lada & Fich 1996).

Obviously, given these considerations, the standard conversion factor may not apply at all. With these caveats in mind, we will in the following assume that the two tracers do not represent the same gas, which would correspond to a total gas mass of at most $3.5 \times 10^9 M_{\odot}$.

4.1.3. Warm ionized gas mass

We can also estimate the mass of ionized gas in 3C 326 N from our SDSS spectra. Assuming case B recombination and following Osterbrock (1989) we can estimate an ionized gas mass, M_{HII} from the H α emission-line luminosity, $\mathcal{L}_{\text{H}\alpha}$, by setting

$$M_{\text{HII}} = \frac{\mathcal{L}_{\text{H}\alpha} m_p}{h \nu_{\text{H}\alpha} \alpha_{\text{H}\alpha}^{\text{eff}} n_e} = 9.73 \times 10^6 \mathcal{L}_{\text{H}\alpha,41} n_{e,100}^{-1} M_{\odot}, \quad (1)$$

where m_p is the proton mass, h is Planck's constant, $\alpha_{\text{H}\alpha}^{\text{eff}}$ and $\nu_{\text{H}\alpha}$ are the effective recombination cross section and the frequency of H α , respectively. $n_{e,100}$ is the electron density in units of 100 cm⁻³. The H α luminosity, $\mathcal{L}_{\text{H}\alpha,41}$, is given in units of 10⁴¹ erg s⁻¹.

In order to estimate extinction-corrected, intrinsic H α luminosities, we measure the H α and H β fluxes from our SDSS spectra and compare with the expected Balmer decrement of H α /H β = 2.9. We find $A_{\text{H}\beta}^{326\text{ N}} = 0.8$ mag. This implies an extinction-corrected H α luminosity of $\mathcal{L}(\text{H}\alpha)_{\text{ext}}^{326\text{ N}} = 2.8 \times 10^{41} \text{ erg s}^{-1}$.

We also need to constrain the electron densities in the optical emission-line gas, which we estimate from the line ratios of the density-sensitive [SII] $\lambda\lambda 6716, 6731$ emission line doublet. Fitting each line of the doublet with Gaussian profiles, we find a line ratio of $R^{326\text{ N}} = 1.3$. This is near the low-density limit, and assuming an electron temperature of 10⁴ K, these line ratios correspond to electron densities $n_e^{326\text{ N}} = 130 \text{ cm}^{-3}$.

With these extinction-corrected H α luminosities and electron densities, and using Eq. (1), we estimate ionized gas masses of $M_{\text{HII}}^{326} = 2 \times 10^7 M_{\odot}$.

4.2. Kinetic energy provided by the radio source

3C 326 has a powerful, large radio source of Mpc size and resides in a relatively low-density environment compared to powerful radio galaxies generally (Stocke et al. 1979; Willis & Strom 1978). Estimating the intrinsic properties of radio jets, in particular their kinetic power and lifetimes, remains a challenge. The synchrotron emissivity of the radio jet depends on the intrinsic jet power and the ambient conditions, and the jet kinetic power is therefore not easily derived. Estimates based on theoretical arguments suggest factors of ~ 10 – 1000 between radio luminosity and kinetic power (e.g. De Young 1993; Bicknell et al. 1997).

Given these uncertainties, it may be best to use empirical estimates of the jet kinetic power. Bîrzan et al. (2004, 2008) estimated the kinetic power of radio sources by comparing the necessary energy to inflate X-ray cavities in galaxy clusters with the luminosities of the radio sources that are inflating them. They find a factor ~ 100 between kinetic and bolometric radio luminosity, with a large upward scatter of up to factors of a few 1000, perhaps suggesting that the correlation is in fact a lower envelope. Using their scaling with the radio luminosity measured at 327 MHz, and measured radio flux, we find kinetic luminosities of $\mathcal{P}_{\text{kjet},327}^{326} = 4 \times 10^{44} \text{ erg s}^{-1}$. For fluxes measured at 1.4 GHz, we find $\mathcal{P}_{\text{kjet},1400}^{326} = 1.3 \times 10^{45} \text{ erg s}^{-1}$. Using the estimate of Merloni & Heinz (2007) instead, which relies on the 5-GHz core radio power, we find $2 \times 10^{44} \text{ erg s}^{-1}$. Willis & Strom (1978) suggest a total energy content of $6 \times 10^{59} \text{ erg}$ in the radio lobes, which would correspond to a kinetic luminosity of $\text{few} \times 10^{44-45} \text{ erg s}^{-1}$ for a fiducial lifetime of the radio source of 10^{7-8} yrs , in good agreement with the previous estimates. The estimates derived with each method change, reflecting the uncertainties of each approach, but the overall result of this section holds, namely, that the kinetic luminosity is of order $\text{few} \times 10^{44-45} \text{ erg s}^{-1}$.

A closely related quantity is the lifetime of the radio source. Jet lifetimes may either be estimated based on radio spectral indices or estimates of the velocity with which the jet expands, the former typically giving significantly smaller values. For 3C 326 specifically, Willis & Strom (1978) carefully investigated the multi-wavelength radio properties finding spectral ages of 1 – $2 \times 10^7 \text{ yrs}$. Using their estimate of the Alfvén speed and size estimate with our cosmology would yield a kinetic age of $6 \times 10^7 \text{ yrs}$ for most parts of the radio source, although a region that is somewhat spatially offset and has a different polarization angle, may be as old as $\sim 2 \times 10^8 \text{ yrs}$ (Willis & Strom 1978). It is unclear whether this is due to an extended activity period, several activity outbreaks, or the second galaxy of the system, 3C 326 S, which also has a radio core. At any rate, the detection of millimeter continuum emission from 3C 326 N and 3C 326 S (Sect. 2.2, see also Fig. 1) implies on-going activity in both nuclei.

4.3. Kinetic energy of the gas

We will now give rough estimates of the related kinetic energies in each gas phase i . The total kinetic energy estimated from the line widths is given by $E_{\text{r,tot}} = 3/2 \sum m_i \sigma_i^2$. m_i is the gas mass in each phase, and σ_i is the velocity dispersion for the ensemble of clouds derived from the widths of the emission lines (and given

in Tables 1 and 3 for CO and the optical lines, respectively), where we set $\sigma = FWHM/2.355$.

From the optical and millimeter spectroscopy we have direct measurements of the line width, which is $FWHM \sim 600 \text{ km s}^{-1}$ for the optical lines, and $FWHM \sim 350 \text{ km s}^{-1}$ for the CO lines. The rotational H $_2$ lines are not spectrally resolved with IRS, yielding an upper limit of $\leq FWHM \sim 2500 \text{ km s}^{-1}$, which is not very constraining. Near-infrared observations of the rovibrational lines would be an important test to infer the dynamical state of the warm molecular gas. The line widths of CO and the optical lines, which trace gas that is colder, and gas that is warmer than the warm H $_2$, respectively, are not very different (Fig. 2). We therefore expect that the line widths of warm H $_2$ will be in the same range.

Since these spectra are integrated, the line widths will be affected by large-scale motion within the potential of the galaxy. Holt et al. (2008) obtained longslit spectra of optical emission lines in 16 nearby powerful radio galaxies, finding that the kinematics are often very irregular and do not appear dominated by rotation. Where they found regular velocity gradients resembling rotation curves, their data suggest that within radii of 2.5 kpc (corresponding to our aperture) we may sample a range of rotational velocities less than 100 – 150 km s^{-1} .

For a measured line width of $FWHM \sim 500$ – 600 km s^{-1} a velocity gradient of $\sim 150 \text{ km s}^{-1}$ subtracted in quadrature will lead to a negligible correction of $\sim 25 \text{ km s}^{-1}$ (35 km s^{-1} for the measured CO line width of $FWHM = 350 \text{ km s}^{-1}$). Therefore we do not believe that gravitational motion will have a large impact on our measurements. With the velocity and mass estimates given above and in Sect. 4, respectively, we obtain a total kinetic energy of $E_{\text{H}_2}^{326} = 3 \times 10^{57} \text{ erg}$ for the cold and warm molecular gas. The ionized gas has a much smaller mass and a negligible kinetic energy of order $5 \times 10^{55} \text{ erg}$. Kinetic energies are summarized in Table 5.

5. A wind without a starburst

5.1. Mass and energy loss rate of the neutral wind

In attempting to estimate the characteristics of the multiphase medium, absorption lines can play an important role. In Sect. 2.6 we described the detection of a significant interstellar component to the Na D absorption line in 3C 326 N with a systematic velocity offset to the blue and a pronounced blue wing. This is very similar to what is frequently found in starburst galaxies (Heckman et al. 2000; Martin 2005, 2006), where blueshifted Na D absorption is commonly interpreted as strong evidence that galaxies with intense star formation are driving energetic outflows.

Similarly for radio-loud AGN, Morganti et al. (2005) give compelling evidence for outflows of neutral material based on studies of HI absorption line profiles at 1.4 GHz. They identify pronounced blueshifted components with velocities of up to $\sim 2000 \text{ km s}^{-1}$ in a number of galaxies, and a clear excess of blueshifted relative to redshifted material. They emphasize that they find blueshifted material in *all* radio galaxies with sufficiently deep HI spectroscopy, suggesting that outflows of neutral gas may be common amongst powerful radio-loud AGN. Three galaxies observed with Spitzer-IRS have also been observed in HI by Morganti et al. (2005), and interestingly the two which have the more pronounced HI absorption have also luminous H $_2$ line emission (Ogle et al. 2010; Haas et al. 2005b), as expected if outflows and H $_2$ line emission are physically related. The relative velocity of the blue wing of the Na D line suggests a terminal

velocity of $\sim -1800 \text{ km s}^{-1}$ for 3C 326 N, within the range found by [Morganti et al. \(2005\)](#).

To estimate the energy and mass loss rates of the outflow, we need to constrain the associated column density of neutral gas. The relationship between the column density of Hydrogen, N_{H} , and that of Sodium, N_{Na} , is determined by the abundance of Na relative to H and the ionization correction for Na (NaI and NaII). If, as is common for starburst-driven winds (e.g., [Heckman et al. 2000](#)), we assume a solar abundance ratio, a depletion factor of 10 ([Morton 1975](#)) or perhaps more ([Phillips et al. 1984](#)), an ionization correction of a factor of 10, and a NaI column density of 10^{14} cm^{-2} , we find a total H column density of $N_{\text{H}} \sim 10^{21.7} \text{ cm}^{-2}$. To be conservative, we will adopt $N_{\text{H}} \sim 10^{21} \text{ cm}^{-2}$ as a fiducial value. This opens the possibility that 3C 326 N may have a significant component of warm neutral gas, but given the absence of HI spectroscopy, the exact amount of this gas is difficult to quantify, in particular, since parts of the Na I could be associated with outflowing molecular gas.

To directly associate the kinematics of the gas with an outflow rate of mass and energy, we assume a simple model of a mass conserving flow with a constant velocity, which extends from some minimal radius to infinity. This gives mass outflow rates of:

$$\dot{M}_{\text{N}_\text{H}} \sim 50 C_f \frac{\Omega}{4\pi} \frac{r}{1 \text{ kpc}} \frac{N_{\text{H}}}{10^{21} \text{ cm}^{-2}} \frac{v}{350 \text{ km s}^{-1}} M_\odot \text{ yr}^{-1}, \quad (2)$$

and energy loss rates of

$$\dot{E}_{\text{N}_\text{H}} \sim 10^{42.5} C_f \frac{\Omega}{4\pi} \frac{r}{1 \text{ kpc}} \frac{N_{\text{H}}}{10^{21} \text{ cm}^{-2}} \left(\frac{v}{350 \text{ km s}^{-1}} \right)^3 \text{ erg s}^{-1} \quad (3)$$

respectively, where C_f is the covering fraction, $\frac{\Omega}{4\pi}$ is the opening angle, v is the outflow velocity. Covering fraction, opening angle and column density are degenerate. However, relevant for our analysis is the product of the three quantities, so that this does not influence our results. But note that our analysis can only be accurate at an order-of-magnitude level.

We have argued that the NaD lines are likely associated with a significant (but difficult to quantify without direct HI observations) reservoir of warm atomic gas. The size of the (marginally) resolved CO emission ($2.5'' \times 2.1''$) is likely similar to the size of the Na D absorbing region. If we take the geometrical mean of the half beam width as the entrainment radius, $\sim 1.8 \text{ kpc}$, allowing for a covering fraction of 0.5 to 1, and corresponding column densities of $10^{21.3-21.7} \text{ cm}^{-2}$, an opening angle of the outflow of π , and an outflow velocity of 350 km s^{-1} corresponding to the offset velocity found with our line fit (and ignoring the Doppler parameter which suggests higher velocities), we find a mass outflow rate of about $30-40 M_\odot \text{ yr}^{-1}$ and an energy loss rate of $\sim 10^{42-43} \text{ erg s}^{-1}$.

In starburst galaxies, the energy loss rates estimated with the same method and assumptions correspond only to a few percent of the injected mechanical power (e.g. [Heckman et al. 2000](#); [Martin 2005](#)). If the same factor approximately applies for 3C 326 N, we would expect a mechanical power of at least $\text{few} \times 10^{43} \text{ erg s}^{-1}$ (Sect. 4.2).

5.2. Outflow energetics

The outflow properties of 3C 326 N are very reminiscent of what is observed in local starburst galaxies (e.g. [Heckman et al. 2000](#); [Martin 2005](#)), which have column densities of $\sim \text{few} \times 10^{21} \text{ cm}^{-2}$, mass and energy outflow rates of a few to a few $10 M_\odot \text{ yr}^{-1}$ and $10^{43} \text{ erg s}^{-1}$, respectively, and reach maximal blueshifts of

$\sim 400-600 \text{ km s}^{-1}$. AGN and starburst activity often coincide making it difficult to uniquely identify the energy source that is driving the wind. For 3C 326 N this is not the case. [Ogle et al. \(2007\)](#) estimated an upper limit of $SFR \leq 0.07 M_\odot \text{ yr}^{-1}$ for the total star formation rate. Assuming that all of this star formation occurs within regions covered by the $3''$ SDSS fibre, this would correspond to a star-formation intensity of $SFI \leq 0.004 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$. This is more than an order of magnitude lower than the $SFI \sim 0.1 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$ threshold found by [Heckman \(2003\)](#) for starbursts that drive winds. We come to a similar conclusion when comparing with the supernova rate expected for constant star formation with $SFR = 0.07 M_\odot \text{ yr}^{-1}$. Using [Bruzual & Charlot \(2003\)](#) we find a supernova rate of $3.5 \times 10^{-4} \text{ yr}^{-1}$. Assuming that all of the “canonical” energy release of a supernova, 10^{51} erg , will thermalize, we find an energy injection rate of $10^{40} \text{ erg s}^{-1}$, about three orders of magnitude lower than the mechanical power of the wind in 3C 326 N or the line emission of the warm ionized and molecular gas. For more realistic thermalization efficiencies of few tens of percent ([Strickland & Heckman 2009](#)), the energy injection from supernovae will be even lower by factors of a few.

In addition, the terminal velocity of -1800 km s^{-1} is $\sim 3-4\times$ greater than terminal velocities typically found in starburst-driven winds (which are of order few 100 km s^{-1} [Heckman et al. 2000](#); [Martin 2005, 2006](#)) and similar to some of the most powerful starbursts (which have star-formation rates orders of magnitude higher than 3C 326). Both arguments indicate that the outflow in 3C 326 N is *not* related to star formation. This velocity is also significantly larger than what we may expect from velocities due to a possible interaction with the nearby galaxy 3C 326 S (see the discussion in [Ogle et al. 2007](#)). The only plausible candidate driving this outflow is a radio-loud AGN.

6. Energy and momentum exchange in the multiphase cocoon

We will now use our observational results to construct a scenario for the interaction between jet and interstellar medium of the host galaxy, which explicitly includes the molecular gas. We will argue that the kinematics and emission-line luminosities of 3C 326 N are most likely related to the energy injected by the radio jet, which is being dissipated by the multiphase interstellar medium of the host galaxy. We describe and quantify the energy flow and associated timescales.

6.1. Energy, mass and momentum flow

Much theoretical effort has been dedicated to describing the interactions of radio jets with the ambient medium (for early studies see, e.g., [Scheuer 1974](#); [Begelman & Cioffi 1989](#)). Observational evidence that jets may have a profound influence on the interstellar medium of their host galaxies has been known for at least two decades (e.g., [van Breugel et al. 1985](#); [Pedlar et al. 1985](#); [Tadhunter 1991](#); [Eales & Rawlings 1993](#)). The “cocoon model” describes interactions between radio jet and ambient gas in form of a “waste energy basket” ([Scheuer 1974](#)) of hot, low-density, but high-pressure material that surrounds the thin relativistic jet. This “cocoon” will expand into the ambient gas and may entrain matter ablated from denser clouds of colder material (e.g., [Begelman & Cioffi 1989](#)), drastically enhancing the efficiency with which the jet interacts with the gas of the galaxy compared to simple interactions along the jet working surface (“dentist’s drill”, [Scheuer 1982](#)). We will now extend this

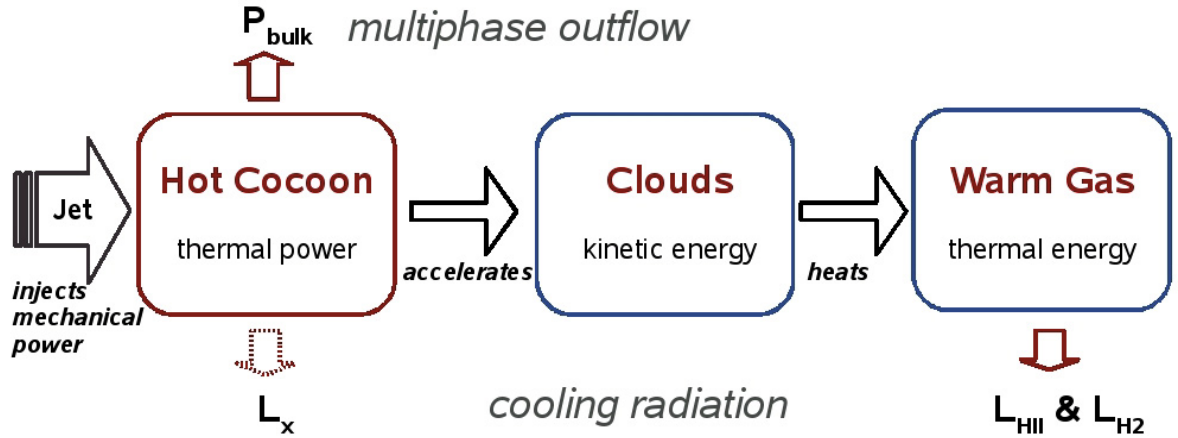


Fig. 8. This diagram outlines the energy flow within the hot “cocoon” that we discuss in Sect. 6.

scenario by explicitly taking into account the energy, mass, and momentum exchange between different gas phases which result from the injection of mechanical energy by the radio source. This scenario represents the synthesis of our observational results discussed in Sects. 3 to 5.

Figure 8 illustrates our basic scenario of the energy and momentum flow in the cocoon. Part of the mechanical energy injected by the radio jet is ultimately transformed into thermal energy of the warm atomic and molecular gas, giving rise to the observed line emission. A part of the jet kinetic power is also translated into thermal and bulk kinetic energy of the hot cocoon plasma (first box in Fig. 8). This plasma is strongly over-pressurized and expands on a timescale shorter than its cooling time, thus driving a net outflow of multiphase gas with outflow rates of a few $\times 10 M_{\odot} \text{ yr}^{-1}$ (Sect. 5). In addition, the ablation of cloud material by the outflowing hot medium may replenish the hot medium of the cocoon, which would help maintaining a high pressure as the cocoon expands, and enhance its lifetime. The energy cascade causes a momentum transfer from large-scale bulk motion to turbulent motion on smaller scales. Dynamical interactions between the different gas phases drive fragmentation of the molecular clouds and turbulent motions between and within individual fragments (second box in Fig. 8). This may lead to entrainment of parts of the warm and cold medium in the hot wind as described for starburst-driven winds (Heckman et al. 2000).

This interaction between the molecular gas and the outflowing plasma creates a physical environment not very different from that produced by the galaxy-wide shock in Stephan’s Quintet (Guillard et al. 2009; Appleton et al. 2006). Similar to the analysis of Guillard et al. (2009), we postulate that turbulent motion in the cocoon drives shocks with velocities that depend on the gas density. In a multiphase medium, differences in gas densities between the cold and hot gas are up to factors of 10^6 . For a given ram pressure, this translates into a factor 10^3 in shock velocity. The shocks maintain the amount of warm molecular and ionized gas that are necessary to explain the observed luminous line emission of the molecular and ionized gas (third box in Fig. 8). Due to the high density, shocks driven into magnetized molecular gas will be slow, with velocities of a few $10 \text{ s of km s}^{-1}$, so that H_2 will not be destroyed, but becomes a main coolant. This is in agreement with our molecular

diagnostic diagram in Fig. 6 and with the pure rotational H_2 line ratios, which are consistent with excitation through slow shocks.

The gas cooling times for these shocks listed in Table 7 are very short, of order 10^4 yrs . In order to maintain the gas at the observed temperatures, the cocoon must inject energy over similar timescales. This is important, since these timescales are significantly shorter than the free-fall times of self-gravitating molecular clouds. This is evidence that the gas cannot form gravitationally bound structures and stars, simply because it is continually being stirred up by mechanical interactions in the multiphase gas which are ultimately powered by the radio source. We will discuss in Sect. 6.3 that the AGN may maintain such conditions over significant timescales ($10^7\text{--}8 \text{ yrs}$), and discuss astrophysical implications in Sect. 7.

6.2. Efficiency of the energy transfer

Simple energy conservation implies that our scenario for powering the line emission and the outflow through mechanical interactions is only realistic if the efficiency of the power transfer in each step is ≤ 1 . We have estimates for the jet kinetic power ($\geq \text{few} \times 10^{44} \text{ erg s}^{-1}$, Sect. 4.2) and the emission-line luminosity of H_2 and HII ($\sim 10^{43} \text{ erg s}^{-1}$). The mechanical power necessary to drive the outflow is similar to the emission-line luminosity at an order-of-magnitude level (Sect. 5). Taken at face value, these estimates indicate that at least $\sim 10\%$ of the jet kinetic luminosity is deposited within the cocoon, which shows that our scenario of jet-powered line emission is indeed energetically plausible. The efficiency of the cocoon in driving an outflow – the ratio between the mechanical power carried by the outflow to the power thermalized in the cocoon – may well be about 1, comparable to that derived from observations of starburst-driven outflows (e.g. M82 Strickland & Heckman 2009). The luminous line emission of 3C 326 N implies that a power comparable to that of the bulk outflow is radiated away due to dissipation in the interstellar medium.

6.3. Dissipation time and length of the H_2 -luminous phase

If the radiation of luminous optical and infrared line emission is due to the dissipation of the kinetic energy of the warm and cold

interstellar medium, then we can roughly estimate the dissipation time of the kinetic energy of the gas, simply by relating the measured kinetic energy and the emission-line luminosity. We will in the following estimate this timescale, and compare with the characteristic timescales of jet activity.

In Sect. 3.3 we found that the ionized gas, although negligible in the mass budget, dominates the radiative energy budget of the warm and cold interstellar medium with a bolometric luminosity of $\sim 1 \times 10^{43} \text{ erg s}^{-1}$, whereas the molecular gas emits a lower luminosity of $1 \times 10^{42} \text{ erg s}^{-1}$. In Sect. 4.3 we estimated that the kinetic energy of the molecular gas is most likely $\sim 3 \times 10^{57} \text{ erg}$, about two orders of magnitude more than that of the warm ionized gas (see also Table 5), and that it is not likely that this energy budget will be dominated by rotation.

We will now constrain the range of plausible dissipation times, assuming that the UV-optical emission of the ionized gas is powered by the turbulent kinetic energy, and fully participates in the dissipation process. In this case,

$$\tau_{\text{diss}} = \frac{3/2 (M_{\text{ion}}\sigma_{\text{ion}}^2 + M_{\text{mol}}\sigma_{\text{mol}}^2)}{\mathcal{L}_{\text{ion}} + \mathcal{L}_{\text{mol}}} \sim 10^7 \text{ yr.} \quad (4)$$

But the dissipation time could be significantly larger if the UV-optical lines are not entirely powered by the turbulent energy. The molecular gas could be in a region where the hot plasma has already been accelerated, so that the kinetic energy of the hot wind would power the line emission through direct interactions between the molecular gas and the surrounding warm and hot gas. In this case, the bulk kinetic energy of the wind would be powering the line emission, not the turbulence of the molecular gas. In the extreme case that the luminosity of the ionized gas is fully dominated by the kinetic power from the outflow, it does not contribute to the dissipation and the timescales simply follow from setting

$$\tau_{\text{diss}} = \frac{3/2 (M_{\text{mol}}\sigma_{\text{mol}}^2)}{\mathcal{L}_{\text{mol}}} \sim 10^8 \text{ yr.} \quad (5)$$

(Note that we included He into our mass budget for both time estimates.) These findings have two interesting consequences. First, the dissipation time is much longer than the cooling time predicted by our shock models for the molecular gas (Sect. 4.1.1), which is of order 10^4 yrs. This may imply that the turbulent environment of the cocoon feeds a mass and energy cycle similar to that described by Guillard et al. (2009) for Stephan's Quintet, where the gas undergoes many episodes of heating and cooling on "microscopic" scales, effectively maintaining an equilibrium between different gas phases on macroscopic scales.

The large mass flow of a few $100 M_{\odot} \text{ yr}^{-1}$ (which we estimated in Sect. 3.3 from the H _{β} luminosity) is a natural outcome of this mass cycle. It is too large to be accounted for by the large-scale bow shock as the cocoon expands through the galaxy, but may plausibly be produced by shocks that are locally generated, as the molecular gas fragments move relative to the low-density, hot medium. Shock velocities of order 250 km s^{-1} inferred from the optical line ratios (Sect. 3.3) are subsonic with respect to the hot gas, but supersonic relative to the warm gas ($T < 10^6 \text{ K}$). Such a cycling between warm and cold gas phases may also be important for the exchange of momentum between the hot plasma and the H₂ gas and thereby for the entrainment of gas into the flow.

Second, a dissipation time of $\sim 10^{7-8}$ yrs is significant compared to the lifetime of the radio jet (of order 10^7 yrs, Sect. 4.2),

or even the duty cycle of jet activity of order 10^8 yrs estimated from observations of "rejuvenated" radio sources (e.g., Schoenmakers et al. 2000). If the dissipation time is similar to the lifetime of the radio source, then the energy content of the gas will reflect the *total energy injected by the radio source*, including the early stages of radio activity when the jet was confined within the inner regions of the galaxy, and when the interaction was likely to be particularly efficient. If it is even longer, then it may influence the interstellar medium and star-formation properties of the massive host galaxies of radio-loud AGN even on timescales beyond their "active" phase. This is possible if the gas luminosity drops at the end of the jet activity period. In this case the dissipation timescales will be longer than our estimates. Addressing this question in detail would require observational constraints of the line emission in galaxies after their radio-loud phase (radio relics) and is beyond the scope of this paper.

7. Molecular gas and star formation

(Cold) molecular gas and star formation are closely related: gas surface densities and star-formation intensities (star-formation rate surface densities) show a close relationship over several orders of magnitude ("Schmidt-Kennicutt relation" Schmidt 1959; Kennicutt 1998). As we discussed previously, in H₂ luminous radio galaxies, however, star-formation rates appear low compared to the amount of available molecular gas. It is therefore interesting to investigate whether these galaxies fall onto the same star-formation law as "ordinary" star-forming galaxies.

7.1. Constructing a Schmidt-Kennicutt-like diagram from PAH and CO line emission

The best way of estimating star-formation rates is, generally speaking, the infrared continuum. However, in powerful radio galaxies the $24 \mu\text{m}$ and $70 \mu\text{m}$ flux scales with AGN power (Tadhunter et al. 2007), likely indicating that much of the dust is heated by the AGN rather than star formation. We will therefore rather use the PAH emission as an approximate tracer of star formation in our galaxies. For the radio galaxies of Ogle et al. (2010) we have direct measurements of the PAH fluxes from the IRS spectra, for star-forming galaxies we will use the $8 \mu\text{m}$ luminosity instead, which in these galaxies is dominated by the $7.7 \mu\text{m}$ PAH feature. We use values corrected for the stellar contribution by Calzetti et al. (2007); Roussel et al. (2007) and have already outlined in Sect. 3.1 how we translate $8 \mu\text{m}$ flux densities in PAH fluxes.

Although PAHs are also not very robust tracers of the star-formation intensity generally, empirically they are found to be equally robust as the $24 \mu\text{m}$ flux when studying the integrated star formation rates in galaxies with high metallicities. (Calzetti et al. 2007). The quality of our optical spectra of 3C 326 N is not sufficient to safely determine a metallicity from the absorption lines, but with its large stellar mass of order $10^{11} M_{\odot}$, 3C 326 N can safely be expected to have a high metallicity. The same applies to H₂-luminous radio galaxies generally.

In Fig. 9 we show a Schmidt-Kennicutt-like diagram based on the PAH luminosity and CO surface brightness for 3C 326 N and other H₂ luminous radio galaxies with published CO observations (Ogle et al. 2010, lists H₂ luminous radio galaxies with CO measurements in the literature), as well as for star forming and AGN host galaxies taken from SINGS (Roussel et al. 2007). For galaxies where CO (and/or PAH) measurements are not spatially resolved, we assume a radius of 2.5 kpc each. We are using

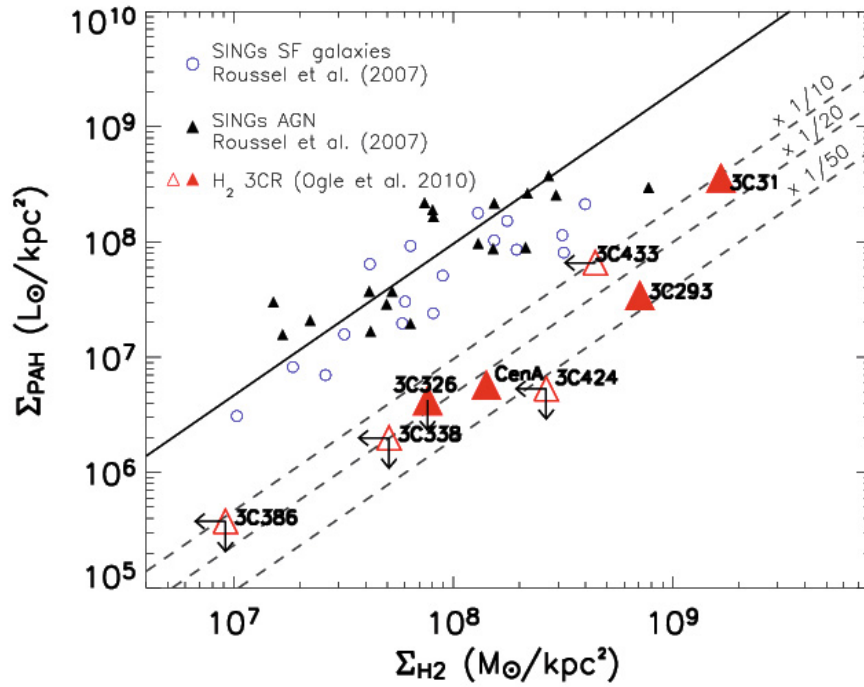


Fig. 9. PAH intensity as a function of molecular gas mass surface density measured from the CO(1–0) emission-line intensity. The black solid line shows the Schmidt-Kennicutt law (Kennicutt 1998), where the star-formation intensity is translated into a PAH intensity using the results of Calzetti et al. (2007). Small black triangles and small blue circles: SINGS star-forming and AGN host galaxies, respectively. Red triangles: 3C 326 N and other H₂ luminous radio galaxies which have factors 10–50 towards lower PAH intensities for a given molecular gas mass (black hatched lines). Filled triangles mark galaxies with spatially resolved CO detections, empty triangles mark galaxies with integrated measurements. Arrows mark galaxies with sensitive upper limits.

the same radius for PAH and CO emission, implying that molecular gas and PAH emission originate from the same region of the galaxy, which is astrophysically plausible.

Using Eqs. (2) and (6) of Calzetti et al. (2007) we derive a calibration of star-formation intensity as a function of 8 μ m luminosity (νL_ν) per kpc² or

$$\log \Sigma_{\text{SFR}} = -45.32 + 1.06 \log S_{8\mu\text{m}} \quad (6)$$

where Σ_{SFR} is the star-formation intensity in $M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$ and $S_{8\mu\text{m}}$ the luminosity at 8 μ m in $\text{erg s}^{-1} \text{ kpc}^{-2}$ corrected for the stellar continuum (see Calzetti et al. 2007, for details). We also use this relationship to re-calibrate the star-formation law of Kennicutt (1998) in terms of PAH luminosity, finding

$$\log S_{8\mu\text{m}} = 31.44 + 1.32 \log \Sigma_{\text{gas}} \quad (7)$$

where Σ_{gas} is the molecular gas surface density in $M_\odot \text{ kpc}^{-2}$. This relationship is somewhat less steep than the original Kennicutt law (which has a power-law index 1.4), simply because PAH surface brightness and star-formation intensity do not scale linearly.

7.2. Is the star-formation efficiency low in H₂ luminous radio galaxies?

The Schmidt-Kennicutt law is shown as the black solid line in Fig. 9, and is a good representation of the SINGS galaxies with CO emission line observations (Roussel et al. 2007). In strong contrast, 3C 326 N as well as the other H₂ luminous radio galaxies shows a pronounced offset by roughly 1–1.7 dex (a factor 10–50) towards lower PAH fluxes, but with a very similar

slope. If the “standard” CO conversion factor roughly applies, and if PAH emission traces star formation in a similar way as in “ordinary” star-forming galaxies, then our result implies that the star formation in H₂ luminous radio galaxies is about a factor 10–50× less efficient than in “ordinary” star-forming galaxies. But even if these assumptions were not strictly appropriate, the basic result would persist, that the conditions of the interstellar medium in 3C 326 N and other H₂ luminous radio galaxies are significantly different from those in galaxies with “ordinary” star formation properties.

7.2.1. Caveats

Figure 9 is based on several assumptions, each of which introduces systematic uncertainties. This is why we prefer not to state a specific offset but rather give a range of possible offsets from the Schmidt-Kennicutt law. We will now discuss these uncertainties.

One obvious caveat in our conclusion is that we only used the CO measurements to estimate a gas mass, neglecting the warm H₂. Including the warm molecular gas in our mass estimate would only increase the offset of the H₂ luminous galaxies relative to the SINGS sample, for example by 0.3 dex for 3C 326 N. Changes in the CO-to-H₂ conversion factor would have to be as large as the offset to move the H₂ luminous galaxies onto the nearby relationship, and would again not change the basic conclusion, namely that the physical gas conditions in these galaxies are markedly different from those in “ordinary” star-forming galaxies. In this case, the CO-to-H₂ conversion factor would have to be *lower* by a factor 30 than in the

SINGS galaxies, and a factor 6 lower than in ULIRGs (Downes & Solomon 1998).

Another possible caveat is that we adopted a fiducial radius of 2.5 kpc for the galaxies where we only have integrated measurements (empty red triangles in Fig. 9). Varying this radius by large amounts (greater than factors 2–3) will mildly affect the position of individual galaxies, but is not sufficient to put them onto the “ordinary” Schmidt-Kennicutt ridge. This limitation can easily be overcome by collecting larger samples with high-resolution, high-quality CO observations. Galaxies shown as red filled triangles have spatially-resolved CO measurements and are not affected by this effect. We adopted the same radii for PAH and CO emission, which corresponds to the astrophysical assumption that both are related to the same star-forming regions.

We may also wonder whether this offset could reflect a net deficit of PAH emission? We will rely on the close analogy with the H₂-luminous shock in Stephan’s Quintet to address this concern. For Stephan’s Quintet, Guillard et al. (2010) show that the PAH and mid-IR continuum associated with the warm H₂ emission is consistent with the expected emission from the warm molecular gas, assuming that the dust-to-gas mass ratio, and the fraction in PAHs and very small grains have roughly the same values as in the Milky Way.

The ratios between H₂, CO and PAH luminosities in 3C 326 are very similar to those measured in Stephan’s Quintet (Fig. 6), so that similar arguments may apply to 3C 326 N. For a standard (Galactic) dust mass fraction in PAHs, the weakness of the PAH emission implies a UV field comparable to that observed in the intergalactic shock in Stephan’s Quintet. The UV intensity in Stephan’s Quintet, measured with GALEX, is not very different from that in the Solar Neighborhood (1.4 in Habing units²). We used Starburst99 (Leitherer et al. 1999) to deduce an upper limit on the UV radiation field from the measured upper limit on the star-formation rate ($0.07 M_{\odot} \text{ yr}^{-1}$, inferred by Ogle et al. 2007, from the PAH and mid-infrared dust continuum of 3C 326 N). Assuming that the molecular gas is within a sphere of 2.5 kpc radius (the approximate extent of the CO emission), we find an upper limit on the UV radiation field of about 1 Habing unit. Thus, the weakness of the PAH and dust mid-IR emission is consistent with the low star-formation rate, and does not require the molecular gas to be PAH poor. Measuring the dust mass and temperature directly from the far-infrared luminosity is now possible with Herschel. This will allow for more robust estimates of the star-formation rates, and give direct constraints on the CO-to-H₂ conversion factor. These measurements will be critical to better estimate the star-formation efficiencies in H₂ luminous galaxies.

7.2.2. Implications

We are not the first to note that star formation in radio galaxies with CO detections appears suppressed relative to radio-quiet galaxies. Okuda et al. (2005) and Papadopoulos et al. (2007) found the same effect for 3C 31 and 3C 293, respectively. Koda et al. (2005) identify star-forming knots embedded in the molecular disk of 3C 31, pointing out that, although the disk appears globally stable against gas collapse and star formation, this is not sufficient to quench all star formation. The position of 3C 31 in Fig. 9 suggests that, nonetheless, the overall star formation efficiency in this galaxy is considerably lower than in “ordinary” star-forming galaxies.

Our previous discussion of how the radio source influences the energy budget of the interstellar medium of 3C 326 N (Sect. 6) suggests that heating through the radio source may be an attractive non-gravitational mechanism, at least in galaxies that host radio-loud AGN, which may enhance the turbulence and heating in a molecular disk, preventing or suppressing gravitational fragmentation and gas collapse and ultimately star formation. In Cen A (NGC 5128) Neumayer et al. (2007) find that the ro-vibrational H₂ emission lines are broader than expected from the stellar velocity dispersion, although they have an overall similar velocity field. This would certainly agree with a scenario where a small fraction of the energy injected by the AGN into the multiphase interstellar medium of the host galaxy will finally contribute to increasing the turbulence in the molecular disk. Detailed follow-up observations of a sufficiently large sample of H₂-luminous galaxies are certainly necessary to substantiate this speculation.

We did not find evidence for positive AGN feedback enhancing the star formation efficiency relative to “ordinary” star forming galaxies, as proposed by, e.g., van Breugel et al. (1985); Begelman & Cioffi (1989); Mellema et al. (2002); Fragile et al. (2004); Croft et al. (2006); Silk & Norman (2009). van Breugel et al. (1985); Schiminovich et al. (1994); Croft et al. (2006); Elbaz et al. (2009) claim evidence for star formation associated with radio jets outside the host galaxy in a few individual nearby systems, which may be triggered by the jet. Indeed, turbulence can trigger star formation locally where gravitationally-bound giant molecular clouds are otherwise not able to form (Klessen et al. 2000). If positive feedback dominated in our galaxies, we would expect an offset to higher star-formation intensities for a given gas surface density in Fig. 9, which is not the case, as all radio galaxies are shifted towards lower star-formation efficiencies.

Our overall results suggest that the suppression or enhancement of star formation depends critically on the details of the “micro-”physics of the gas on small scales, which is beyond the capabilities of current numerical models and requires detailed observations of the multiphase gas in AGN host galaxies, which are becoming possible only now with Spitzer, Herschel, ALMA, and JWST. In particular, it is unclear whether our results can be easily extrapolated to (radio) galaxies at high redshift, which have copious amounts of molecular gas traced through CO line emission (e.g., Papadopoulos et al. 2000; De Breuck et al. 2003, 2005; Nesvadba et al. 2009), but whose gas conditions are likely very different from those in 3C 326 N. If the kinetic energy in these galaxies can be dissipated rapidly enough to allow for gas collapse and star formation, then feedback may be positive.

8. Implications of this scenario for galaxy evolution

The energy injected by powerful AGN into the interstellar medium and halo of galaxies may play an important role in determining the characteristics of galaxies in the local Universe. For example, the high metallicities, luminosity-weighted stellar ages, and relative abundances of α elements relative to iron suggest rapid, and truncated star formation in the early Universe followed by a long phase of (mostly) passive evolution (e.g., Pipino & Matteucci 2004) for massive galaxies. These observations are consistent with a phase of powerful AGN driven outflows in the early Universe. In fact, studies of powerful radio galaxies at $z \sim 2$ with rest-frame optical integral-field spectroscopy reveal energetic outflows which have the potential of removing a significant fraction of the interstellar medium of a massive, gas-rich galaxy within the short timescales necessary to explain the

² The Habing field is equal to $2.3 \text{ erg s}^{-1} \text{ cm}^{-2}$ at $\lambda = 1530 \text{ \AA}$ (Habing 1968).

super-solar $[\alpha/\text{Fe}]$ ratios and old luminosity weighted ages observed in massive ellipticals (Nesvadba et al. 2006, 2007, 2008). This “quenching” of star formation by powerful radio jets is in broad agreement with theoretical models explaining the characteristics of massive galaxies. However, in addition to this quenching phase, the radio-loud AGN may also assist in maintaining low star-formation rates over cosmological timescales by inhibiting subsequent gas cooling – “maintenance phase”. This last phase is important since, even in the absence of mergers, subsequent gas infall and return from the evolving stellar population will replenish the reservoir of cold gas which must be prevented (at least partially) from forming stars.

In the scenario we presented above, roughly equal amounts of energy are being dissipated through turbulence, and are powering an outflow of warm neutral and ionized gas. Gas that does not escape from the halo of the host galaxy, will likely cool and rain back onto the galaxy. For cool-core clusters, Revaz et al. (2008); Salomé et al. (2008) propose that molecular filaments may represent gas that has been lifted from the galaxy, has cooled, and may be “raining back down” into the deepest part of the gravitational potential. A similar mechanism may apply to individual galaxies like 3C 326 N. In addition, the stellar population will continue to feed the interstellar medium with material which will also cool and descend into the potential well, if the material will not have been ablated previously. This may once again fuel an AGN, leading to a self-regulating AGN fueling cycle, even in the absence of galaxy merging.

We have so far focused our discussion on 3C 326 N which is the most extreme H_2 luminous radio galaxy known and therefore well suited to study the physical mechanism responsible for the H_2 line emission. However, galaxies are complex astrophysical objects, where a wide spectrum of physical and astrophysical phenomena may act in parallel. In order to illustrate how different formation histories may lead to different observational signatures within a common physical framework, we will in the following contrast 3C 326 N with 3C 293 at $z = 0.045$. We have chosen 3C 293 because it has particularly luminous CO line emission (Evans et al. 1999, and unlike 3C 326) and with CO line ratios suggesting the molecular gas is highly excited (Papadopoulos et al. 2008). It also has a significant outflow of neutral gas (Morganti et al. 2003, 2005; Emonts et al. 2005). Its H_2 emission-line luminosity, warm molecular gas mass and optical line ratios are very similar to those of 3C 326 N (Ogle et al. 2010), which suggests that 3C 293 may be a “gas-rich analog” and thus a foil of 3C 326 N.

8.1. Differing star-formation histories: clues to the importance of molecular gas content?

3C 326 N and 3C 293 have very different star-formation histories. The spectrum of 3C 326 N is consistent with an old stellar population with an age of $>10^{10}$ yrs. At most a small fraction of the total stellar mass, $\leq 5\%$, formed recently ($\sim 1\text{--}2 \times 10^9$ yrs; Fig. 7). Within the $3''$ aperture of the SDSS fiber, this would correspond to $3 \times 10^9 M_\odot$ of stars formed during the last 1–2 Gyr, implying a star-formation rate of about $1 M_\odot \text{ yr}^{-1}$ for a constant star-formation history. We note that this is more than a factor 10 greater than the upper limit on the current star-formation rate of $\leq 0.07 M_\odot \text{ yr}^{-1}$ estimated from the infrared emission.

For 3C 293 we find a significantly more complex star-formation history (see also Tadhunter et al. 2005). Namely $\sim 80\%$ of the stellar mass of 3C 293 was formed at high redshift, $\sim 20\%$ were formed in a more recent star-formation episode about $1\text{--}2 \times 10^9$ yrs ago (Tadhunter et al. 2005, found similar

results). In addition, the equivalent widths and ratio of the Ca H+K absorption lines require a very young population with an age of $\sim 10^7$ yrs, consistent with the starburst implied by far-infrared luminosity (Papadopoulos et al. 2008). The current burst contributes $<1\%$ to the total mass of 3C 293, and the star-formation rate of $SFR_{\text{popsyn}}^{293} \sim 4 M_\odot \text{ yr}^{-1}$ is broadly consistent with the current $SFR_{\text{IR}}^{293} = 7 M_\odot \text{ yr}^{-1}$ estimated from the infrared luminosity of 3C 293 (Papadopoulos et al. 2008). To evaluate whether this fit is unique, we tested alternative star-formation histories with only one or two of the three populations. Figure 7 illustrates that the three-component fit indeed is a significantly better representation of the data. The population synthesis fits also yield stellar mass estimates, but we need to correct for the $3''$ fibre size of the SDSS, which is much smaller than the size of the galaxies. Doing this, we find stellar masses of $M_{\text{stellar}}^{326\text{N}} = 3 \times 10^{11} M_\odot$ and $M_{\text{stellar}}^{293} = 7 \times 10^{11} M_\odot$ for 3C 326 N and 3C 293, respectively.

8.2. Origin of the gas

3C 293 has a $\sim 10\times$ larger reservoir of gas traced through CO line emission than 3C 326 N. What is the likely origin of the gas in these galaxies? Both galaxies have nearby galaxies with which they are perhaps interacting. For the pair 3C 326 N/S, we find a very low gas mass and red optical colors for both galaxies, suggesting this is a gas-poor system. Indeed our estimate of the stellar and gas mass suggests a gas fraction of only $\sim 1\%$. The star-formation history of 3C 326 N appears quiescent and does not indicate that the galaxy was undergoing a starburst due to the interaction. Nonetheless, we may expect the accumulation of a significant amount of cold gas due to mass loss from its stellar population ($\sim 1 M_\odot \text{ yr}^{-1}$) as well as perhaps accretion from the surrounding halo. How much gas will this likely be?

We use the analysis of Kennicutt et al. (1994) to estimate the amount of gas returned by a single-age stellar population into the interstellar medium over 10 Gyr of passive evolution. Kennicutt et al. (1994) find that depending on the details of the star-formation history and initial mass function, as much as 30–50% of the stellar mass formed in the burst may be returned into the ISM during 10 Gyr. From their Fig. 8 we estimate that the gas return after the first 0.5–1 Gyr will be of order a few percent of the stellar mass. For the stellar mass of 3C 326 N, and ignoring any other mechanism like subsequent star formation or feedback, this would correspond to a total gas mass of several $10^9 M_\odot$ up to $\sim 1 \times 10^{10} M_\odot$, factors of a few more than the amount of cold and warm gas we observe in 3C 326 N. In addition, with an infall rate of $\sim 0.1\text{--}1 M_\odot \text{ yr}^{-1}$ of gas accreted from the halo (which appears plausible for early and late-type galaxies; Sancisi et al. 2008) over 10^{10} yrs, this gas mass may roughly double. An infall rate of $\sim 0.1 M_\odot \text{ yr}^{-1}$ of neutral gas has also been estimated by Morganti et al. (2009) from the observation of a narrow, redshifted HI cloud seen in absorption and emission in the nearby, radio-loud early-type galaxy NGC315.

Hence, each of these processes alone could easily explain the observed gas mass of 3C 326 N. For 3C 293 however, similar estimates of stellar mass loss and gas accretion would be inefficient to explain the amount of gas necessary for forming the $\sim 10^{11} M_\odot$ of stellar mass during the last Gyr, which is certainly consistent with the assumption of a merger-triggered starburst for this galaxy. So the difference could be in the “mass accumulation histories” of these two AGN.

8.3. Maintaining the low fraction of recent star-formation

Despite these plausibly different accretion histories, both of the galaxies apparently have low star-formation efficiencies. We estimated that a total of $1\text{--}2 \times 10^{10} M_{\odot}$ of warm/cold gas would accumulate in a massive early-type galaxy such as 3C 326 N over a Hubble time while 3C 293 acquired its gas during an interaction/merger. Is it plausible that the gas in both sources will be heated and substantial fractions removed by the mechanical energy of the jets?

Best et al. (2005) find that the number of radio sources is a strong function of radio power and stellar mass of the host galaxy for a sample of 2000 early-type galaxies with FIRST and NVSS observations taken from the SDSS. For example, for galaxies with stellar mass of $\sim 3 \times 10^{11} M_{\odot}$ they estimate that $\sim 10\%$ of all galaxies have radio powers $\geq 10^{24} \text{ W Hz}^{-1}$, and propose that this may represent a duty cycle, where any given galaxy of this stellar mass will host a similarly powerful radio source for 10% of the time.

Statistically speaking, over 10 Gyr, a given AGN in a few $\times 10^{11} M_{\odot}$ galaxy would be active for a total of $\sim 10^9$ yrs (this total “activity period” may consist of many radio-loud phases with intermediate, quiescent phases). With the same reasoning as in Sect. 4.2 we estimate that a power $\geq 10^{24} \text{ W Hz}^{-1}$ measured at 1.4 GHz will correspond to a kinetic power of order $10^{43} \text{ erg s}^{-1}$, equivalent to a total energy of a few $\times 10^{59} \text{ erg}$ for a total activity time of 10^9 yrs (about 10% of a Hubble time). A few $\times 10^{58} \text{ erg}$ of energy are necessary to unbind $10^{10} M_{\odot}$ in gas from the potential of a galaxy with few $\times 10^{11} M_{\odot}$ in stellar mass (Morganti et al. 2005; Nesvadba et al. 2006, 2008). Based on these simple energy considerations, it appears overall plausible that AGN in massive galaxies may regulate gas cooling through the energy injected by their radio sources over a Hubble time as expected for the “maintenance” mode.

However, in addition to the energy requirement, we also have a timescale requirement, since gas cooling must be inhibited inbetween phases of radio-loud AGN activity, if AGN are to shape the properties of the ensemble of (massive) galaxies. Several arguments may suggest that this could indeed be possible. First, the dissipation timescales we found in Sect. 6.3 of order $10^{7\text{--}8}$ yrs imply that significant fractions of the molecular gas will remain warm during all of the lifetime of the radio jet, and possibly also for a significant time afterwards (if the upper estimate, albeit not very precise, is more appropriate). Interestingly, studies of “rejuvenated” jet activity suggest timescales of about 10^8 years between activity episodes (Schoenmakers et al. 2000), similar to the upper range of the H₂ dissipation time. Second, the mechanical energy injected by radio-loud AGN is sufficient to accelerate and perhaps remove significant amounts of gas. Even if parts of the entrained material will not reach escape velocity, its density will decrease due to the larger volume. The mean free path of particles between collisions will be greatly increased, making the dissipation timescales accordingly longer and delaying the time until this gas will cool and rain back onto the galaxy. Third, the expelled gas may be reheated by mixing with the hot halo gas. Fourth, the molecular gas we observe may only be transitory, where the molecules are formed by the ram pressure of diffuse gas (Glover & Mac Low 2007) as a result of the dissipation of the turbulent energy. This process does not necessarily lead to the formation of gravitationally bound clouds, in which case the H₂ destruction through photodissociation may dominate over the H₂ formation, when the turbulent and thermal pressure in the cocoon drop.

9. Summary

We presented a detailed analysis of the physical gas conditions in the nearby powerful, H₂-luminous radio galaxy 3C 326 N, which does not show the signatures of active star formation in spite of few $\times 10^9 M_{\odot}$ in molecular gas. Our main goals were to investigate the gas conditions in this galaxy, to unravel the astrophysical mechanism which powers the remarkably bright mid-infrared H₂ emission, and to elucidate why this galaxy is not forming stars in spite of a considerable reservoir of molecular gas. To this end, we combined newly obtained CO(1–0) millimeter spectroscopy of 3C 326 N obtained at the Plateau de Bure Interferometer with the Spitzer-IRS spectroscopy by Ogle et al. (2007, 2010) and optical spectra from the SDSS. Our main conclusions are as follows:

1. We compare gas masses for warm and cold gas, estimated from Spitzer mid-infrared spectroscopy and IRAM millimeter imaging spectroscopy. We find that most of the molecular gas in 3C 326 N is warm ($\sim 2 \times 10^9 M_{\odot}$, compared to $1.5 \times 10^9 M_{\odot}$ estimated from our CO(1–0) observations for a “standard” CO-to-H₂ conversion factor). This ratio of warm to cold gas mass is about 1 to 2 orders of magnitude larger than that found in star-forming galaxies, indicating that the gas is in a distinct physical state, which may account for the low star-formation efficiency.
2. We introduce a new “molecular” diagnostic diagram based on the pure-rotational H₂, CO and PAH emission to show that most of the line emission from molecular gas in 3C 326 N is not produced by UV heating. We argue that the gas is likely to be powered by the dissipation of mechanical energy through shocks. The same is found for the ionized gas.
3. Interstellar Na D absorption marks an outflow of neutral gas at velocities of up $\sim -1800 \text{ km s}^{-1}$, and most likely mass and energy loss rates of $30\text{--}40 M_{\odot} \text{ yr}^{-1}$ and $\sim 10^{43} \text{ erg s}^{-1}$, respectively. These values are similar to those found in starburst-driven winds, but this is the first time that such an outflow is detected in the Na D line of a galaxy which does not have strong star formation. The star-formation intensity in 3C 326 N is orders of magnitudes below what is necessary to drive a wind. Similarly, the line profile cannot be explained through the interaction between 3C 326 N and 3C 326 S.
4. Based on these observations we propose a scenario where the outflow and H₂ line emission are intricately related. It represents an extension of the well-explored “cocoon”-model of interactions between radio jets and the ambient gas, and includes the physics of the molecular gas. In this scenario, the H₂ line emission is powered by turbulence induced within dense clouds that are embedded in the expanding cocoon, with a dissipation time of $\sim 10^{7\text{--}8}$ yrs. Dissipation times of 10^8 yrs are in rough agreement with the duty cycle of jet activity estimated from rejuvenated radio sources.
5. Comparing PAH and CO surface brightness (in analogy to the “Schmidt-Kennicutt” diagram), we find a significant offset between 3C 326 N and other H₂-luminous galaxies towards lower PAH surface brightnesses. This may suggest that star-formation efficiencies in these galaxies are lower by roughly a factor $\sim 10\text{--}50$ than those in “ordinary” star-forming galaxies.
6. Generalizing our results for 3C 326 N we find that outflows during similar radio-loud episodes in massive galaxies may balance the secular supply in cold gas through accretion and the mass return from evolved stars over a Hubble

time. If radio-activity is a common, but episodic property of most massive early-type galaxies as suggested by Best et al. (2006), then the long dissipation times of up to $\sim 10^8$ yrs may have consequences for the population of massive galaxies as a whole.

We emphasize that this analysis can only be the first step towards an understanding of how radio-loud AGN regulate the physical conditions of the molecular gas and ultimately star formation in massive galaxies. It illustrates the importance of following a multi-wavelength approach if we seek to relate the physics and astrophysics of AGN feedback with the physical conditions of the interstellar medium including molecular gas in the host galaxy and the regulation of star formation.

Acknowledgements. We would like to thank the staff at IRAM for carrying out the observations. We are particularly grateful to the referee, C. De Breuck, whose comments helped significantly improve the paper, and to Luc Binette and Geoff Bicknell for helpful discussions. This work was supported by the Centre National d'Etudes Spatiales (CNES). N.P.H.N. also acknowledges financial support through a fellowship of the Centre National d'Etudes Spatiales (CNES). IRAM is funded by the Centre National de Recherche Scientifique, the Max-Planck Gesellschaft and the Instituto Geografico Nacional. This work is partly based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, Caltech, under NASA contract 1407.

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